Control over Wireless Networks

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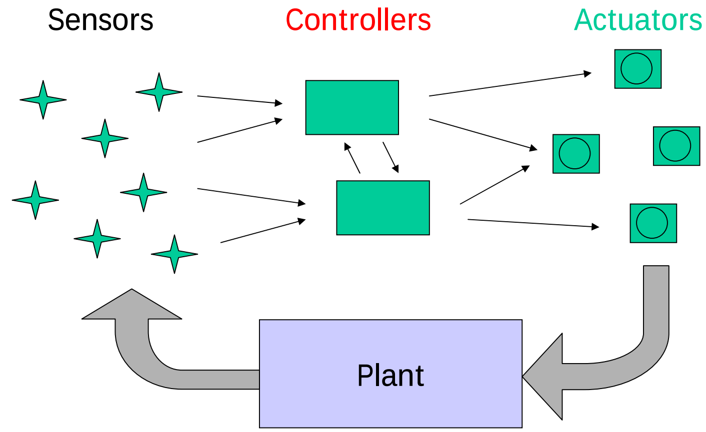
Wireless control system



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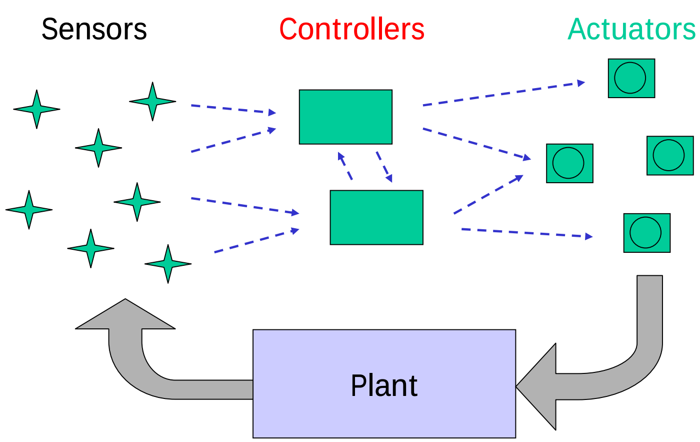
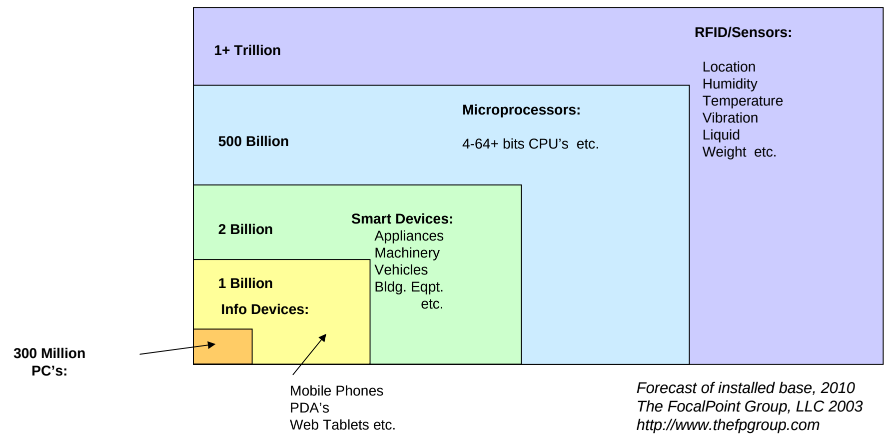


Wireless control systems everywhere

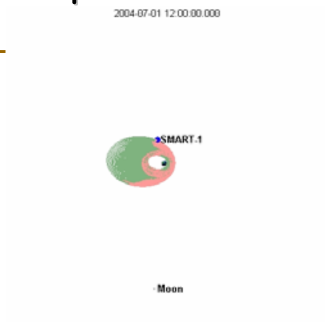
Machine-to-machine device population forecast 2010

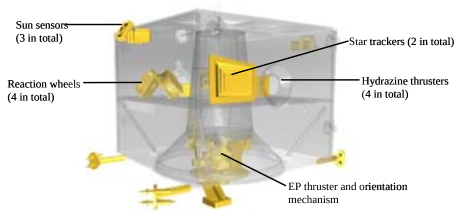


Forecast of installed base, 2010
The FocalPoint Group, LLC 2003
http://www.thefpgroup.com

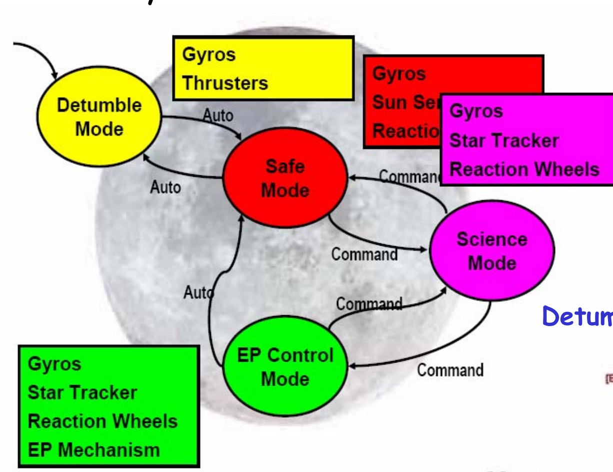
Control of the SMART-1 spacecraft

- First European lunar mission, launched Sep 2003
- Go to the moon using electric primary propulsion
  - Thrust 68 mN, 410 days to reach moon orbit

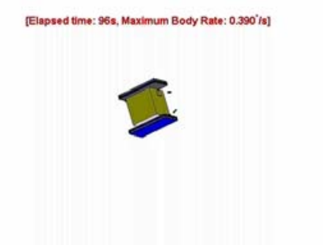




Hybrid control of orbit and attitude



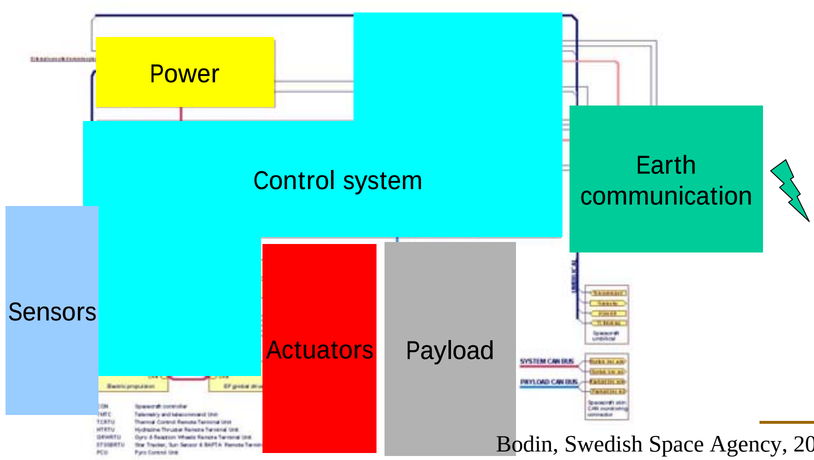
Detumble Mode → Safe Mode



Switch between different control configurations depending on commands and autonomous actions

Architecture of SMART-1 spacecraft

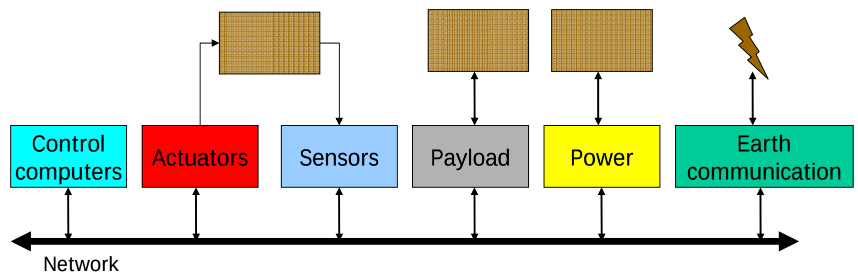
- A networked control system with tight interactions between control systems and other units



Architecture of SMART-1 spacecraft

Networked control architecture gives efficient development and flexible operation

Wired and wireless communication systems influence control performance



Networked control pros and cons

Pros

+ Increased flexibility in design and operation
+ Reduced installation and maintenance costs

Cons

- Higher system complexity
- Larger implementation uncertainty
- Limited communication capabilities
- New energy constraints
- Vulnerable to security flaws

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Illustrate through applications, research problems and potential solutions

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New functionality

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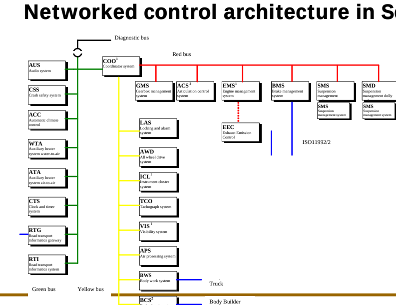
Wireless information systems for improved fuel efficiency in vehicles

- Predict road and driving conditions based on wireless information systems
  - Congestion info through RDS, digital maps, GPS
- Control vehicle subsystems to improve fuel efficiency
  - Cruise control, automated gear shifting, auxiliary systems

Networked control architecture in Scania truck



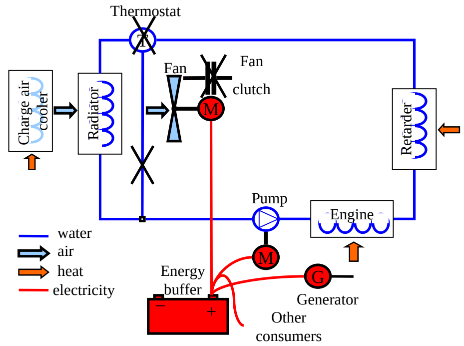
Optimal control of cooling system based on road profile ahead and predicted driver

$$\min_{u \in U} \int_{t_i}^{t_f} \delta(t) u_3(t) dt$$
$$\dot{x} = f(x, u, v)$$
$$x \in X$$

States
x_1 – *cooling temp*
x_2 – *state of charge*

Inputs
u_1 – *pump speed*
u_2 – *fan speed*
u_3 – *generator power*

External influences
v_1, v_2 – *heat*
v_3 – *speed*
v_4 – *el. consumption*



[Pettersson & J, 2006]

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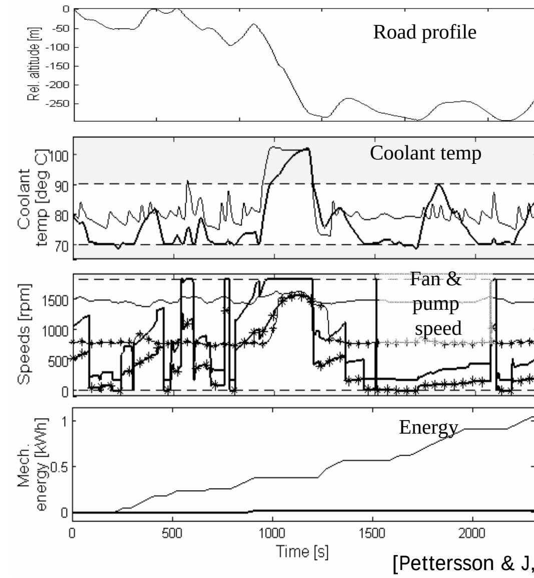

[Pettersson & J, 2006]

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Remove cabling

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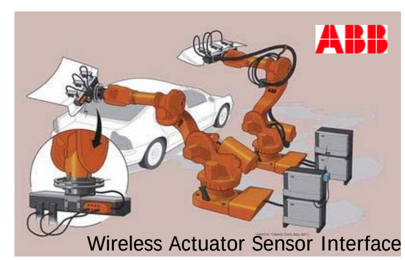
Reduce maintenance through wireless

- Communication cabling in robots is subject to heavy wear and therefore requires frequent maintenance
- Replace wires between robot controller and gripper through wireless communication

Removing cables undoubtedly saves cost, but often the real cost gains lie in the radically different design approach that wireless solutions permit. […] In order to fully benefit from wireless technologies, a rethink of existing automation concepts and the complete design and functionality of an application is required.

Jan-Erik Frey, ABB



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Analyze scalability

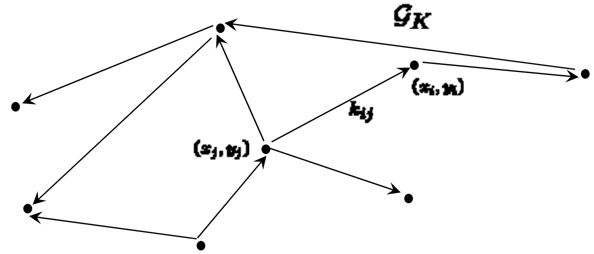
Local rules for global properties

- Distributed coordination of large set of agents

$$x_i(t+1) = x_i(t) + u_i(t)$$

$$u_i(t) = \sum_{j=1}^{N} k_{ij} x_j(t)$$

$$i = 1, \dots, N$$



- How does consensus algorithms scale with network size?

$$x_i^+ = x_i + \frac{1}{\mathrm{indeg}(i)} \sum_{\substack{j \neq i \\ (j,i) \in \mathcal{E}}} (x_j - x_i).$$

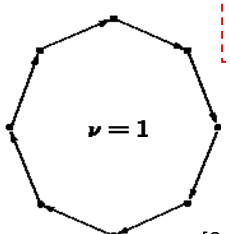
Consensus under symmetries

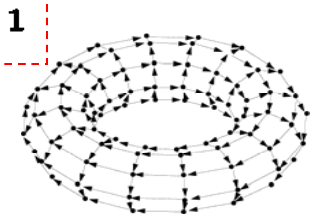
$$x(t+1) = (I+K)x(t)$$

$$\rho = \inf_K \max\{|\lambda| : \lambda \in \sigma(I+K), \lambda \neq 1\}$$

Let the communication network be described by a Cayley graph $\mathcal{G}_K$ and let $\nu > 0$ the in-degree of each vertex of such graph then

$$1 - \frac{C}{N^{2/\nu}} \leq \rho < 1$$



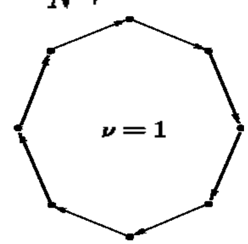


$\nu = 2$

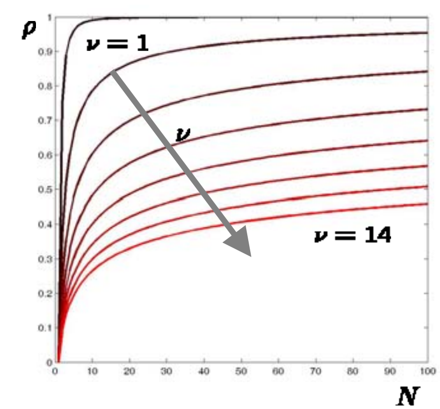
[Carli et al., 2006; Speranzon, 2006]

Consensus under symmetries

$$1 - \frac{C}{N^{2/\nu}} \leq \rho < 1$$



If ν is fixed and $N \to +\infty$ then $\rho \to 1$



Trade off between communication and performance:

- Static symmetric communication graphs gives slow convergence
- Random graphs gives faster convergence

[Carli et al., 2006; Speranzon, 2006]

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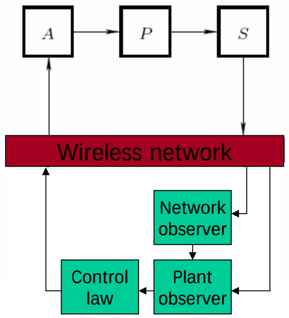
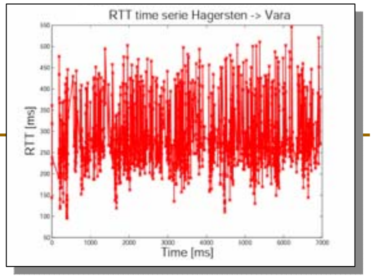
Compensate network variations

Network-aware control architecture

- Controller should adapt to changing network conditions
- Estimate network states
  - Network delay
  - Data loss probability
  - Bandwidth



Delay estimation



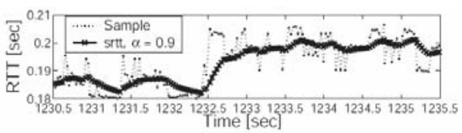
- Internet round-trip time (RTT) data are noisy with piecewise constant average
- Complex network dynamics hard to model
- RTT estimation in TCP:

$$\hat{x}_t = \alpha \hat{x}_{t-1} + (1-\alpha) y_t$$

- Improved estimation thru Kalman filter with hypothesis test (CUSUM filter)

$$\hat{x}_t = \hat{x}_{t-1} + K_t(y_t - \hat{x}_{t-1})$$
$$K_t = \frac{P_{t-1}}{P_{t-1} + R_e}$$
$$P_t = (1 - K_t)P_{t-1} + R_v$$
$$\epsilon_t = y_t - \hat{x}_{t-1}$$
$$g_t = \max(g_{t-1} + \epsilon_t - \xi, 0)$$
$$\delta_t = 1 : R_v \neq 0, \text{alarm if } g_t > h$$
$$\delta_t = 0 : R_v = 0$$

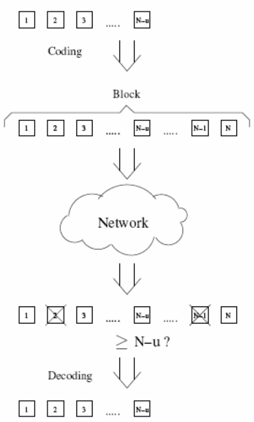
After an alarm, reset $g_t = 0$



[Jacobsson et al., 2004]

Controlled data loss

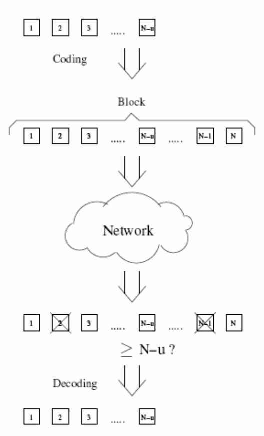
- Compensate data loss through added redundancy
- Base amount of redundancy on feedback information from decoder
  - Adaptive forward error correction

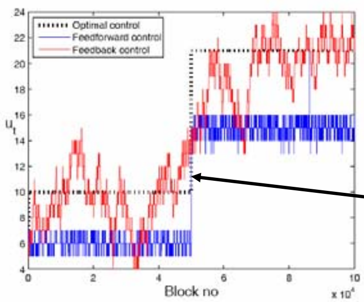


Controlled data loss

- Extremum-seeking control of redundancy:

$$u_{t+1} = u_t - \beta \operatorname{sgn}(\Delta c_t \Delta u_t)$$





Track network variations through variable redundancy

[Flärdh et al., 2005]

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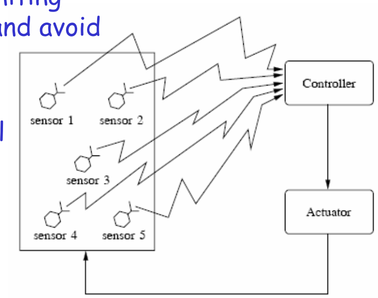
Efficient control strategies

Control under limited communication and sensor resources

Objective: Attenuate disturbances while limiting sensor transmission (to extend lifetime and avoid congestion)

Approach: Event-based sensing with optimal use of communication bandwidth



Remarks

- "Don't fix it, if it ain't broken" (Åström)
- Periodically sampled sensors may waste resources
- Uniform quantization is seldom optimal

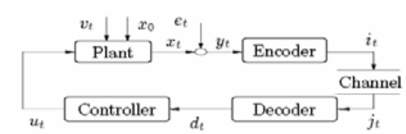
Encoder-decoder design for event-triggered feedback control over bandlimited channel

Optimize closed-loop performance based on plant model and disturbance statistics

$x_{t+1} = ax_t + u_t, \quad |a| < 1$

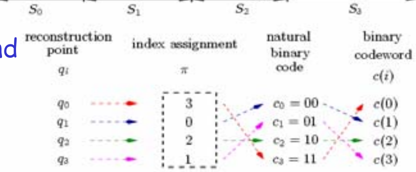
Known pdf p_{x_0}

Minimize $\sum_{t=0}^{T} E\{x_t^2 + \rho u_t^2\}$



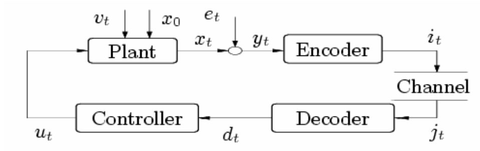
Communication system

Optimize encoder (encoder regions) and decoder (reconstruction points)

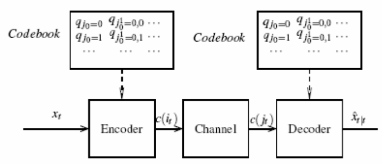


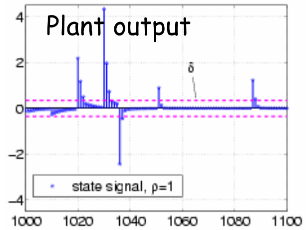
[Bao et al., 2006]

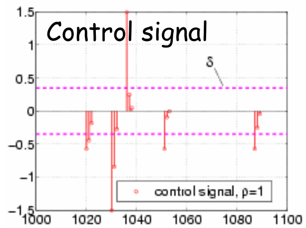
Encoder-decoder design for event-triggered feedback control over bandlimited channels



- Train encoder and decoder through sequential Monte Carlo estimation







[Bao et al., 2006]

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Illustrate through applications, research problems and potential solutions

Conclusions

- Control over wireless networks has a growing domain of application, e.g., industrial automation, vehicle control
- Several open research problems related to architecture, complexity, reliability and security
- Need for integrated approaches:
  - Control-aware networking
  - Network-aware control
- Challenge traditional methodologies in control and communication

Slides and papers at
http://www.ee.kth.se/~kallej

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