Industrial Applications of Networked Control

Karl H. Johansson
ACCESS Linnaeus Center
Royal Institute of Technology
Stockholm, Sweden

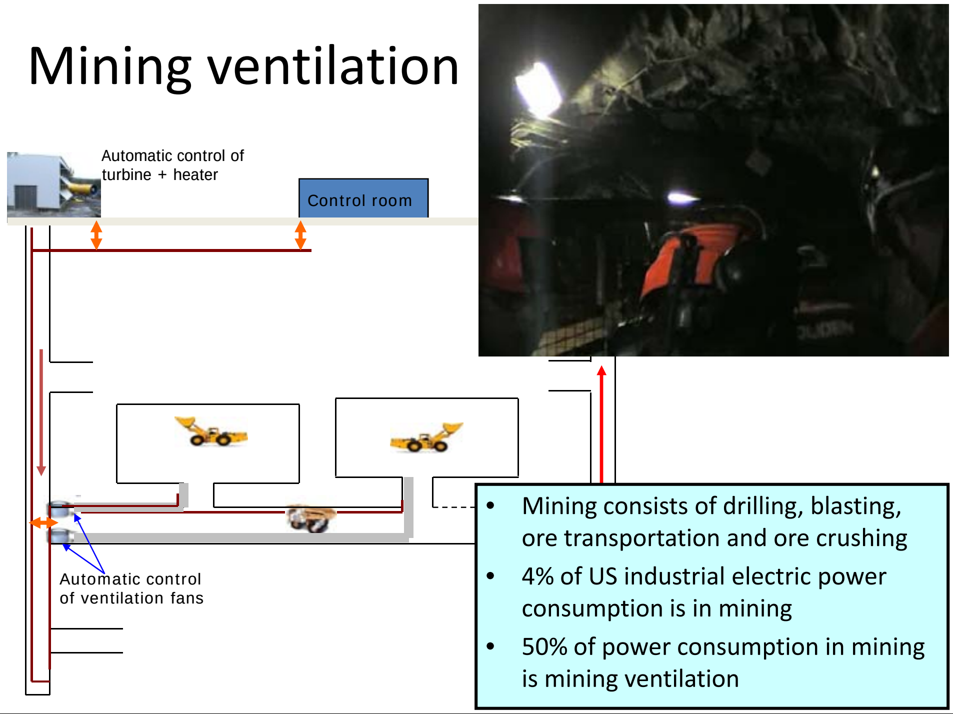
Joint work with Maben Rabi, Mikael Johansson,
Chithrupa Ramesh, Alexandre Seuret, Emmanuel Witrant

ACC 2008, Seattle, WA

Emerging applications

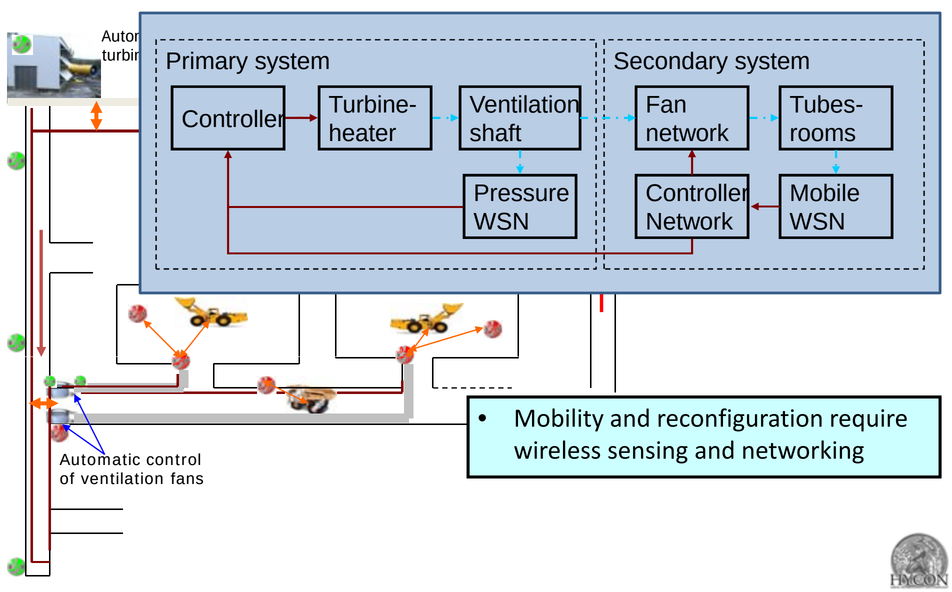
- Wireless **mining** ventilation control
- Wireless control of flotation process
- **Vehicle** fuel efficiency using networked sensing
- **Disaster relief** support using mobile relay nodes
- **Surveillance** with networked vehicles

Mining ventilation



- Mining consists of drilling, blasting, ore transportation and ore crushing
- 4% of US industrial electric power consumption is in mining
- 50% of power consumption in mining is mining ventilation

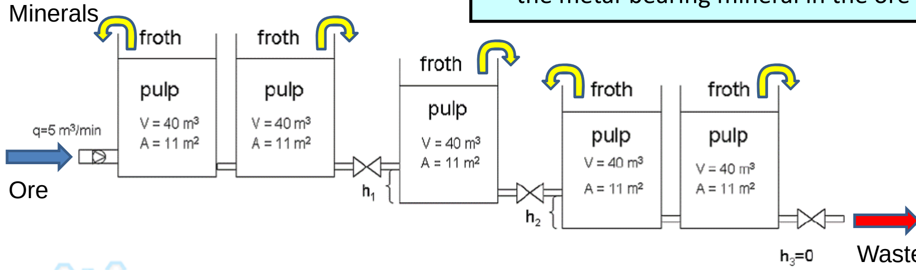
Wireless mining ventilation control



- Mobility and reconfiguration require wireless sensing and networking

Froth flotation process

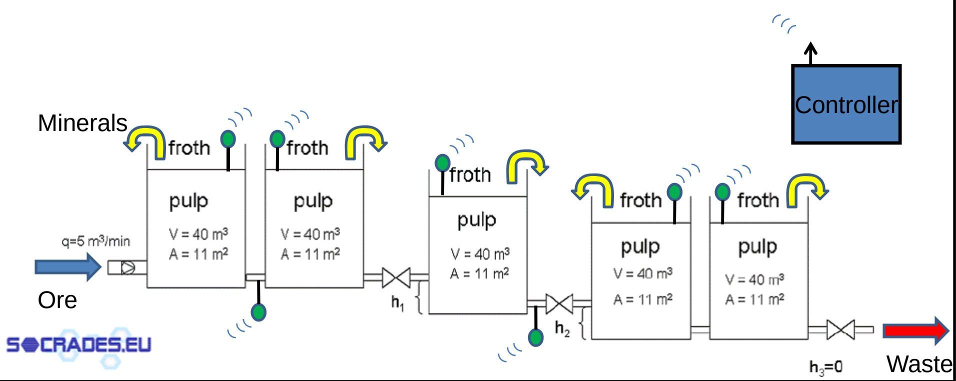
- Froth flotation process concentrates the metal-bearing mineral in the ore



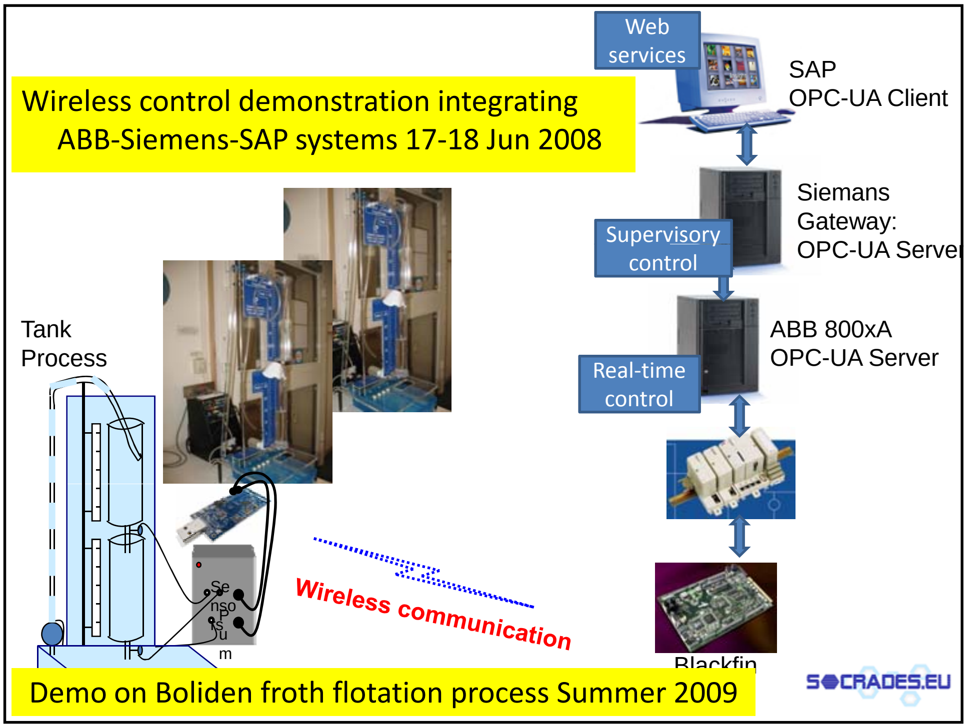
SOCRADES.EU

Wireless control of flotation process

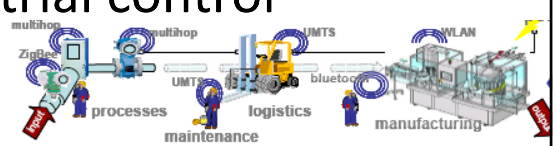
- Level and flow sensors are used for regulating flotation process using SISO PID controllers
- Wireless sensors enable more flexible control strategies



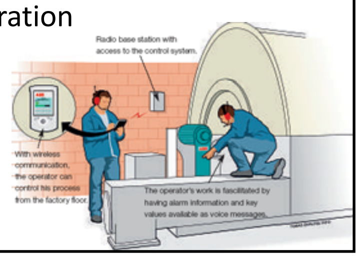
SOCRADES.EU



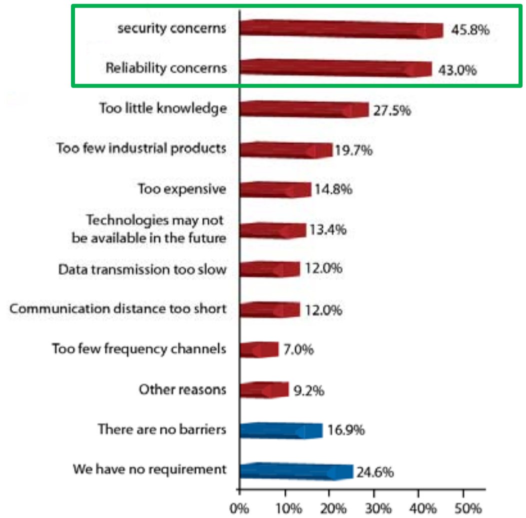
Benefits of wireless networking in industrial control



- **Cost**
  - Reduced wiring
  - Reduced installation work
- **Flexibility**
  - Less physical design limitations
  - More mobile equipment
  - Faster commissioning and reconfiguration
- **Reliability**
  - No cable wear and tear
  - No connector failure



Barriers against wireless networking in industrial control

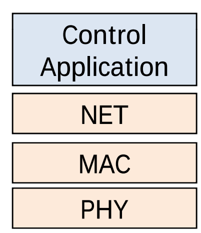


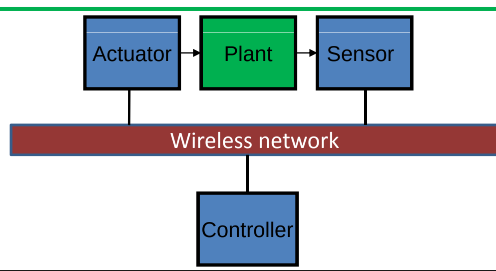
"Market pulse: Wireless in industrial systems: cautious enthusiasm", Industrial Embedded Systems, Winter 2006

A communication or a control problem?

Approaches to control over wireless networks

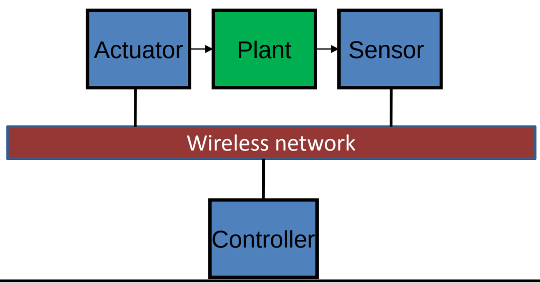
1. Communication protocol suitable for control
2. Control application that compensates for communication imperfections
3. Integrated design of control application and communication layers





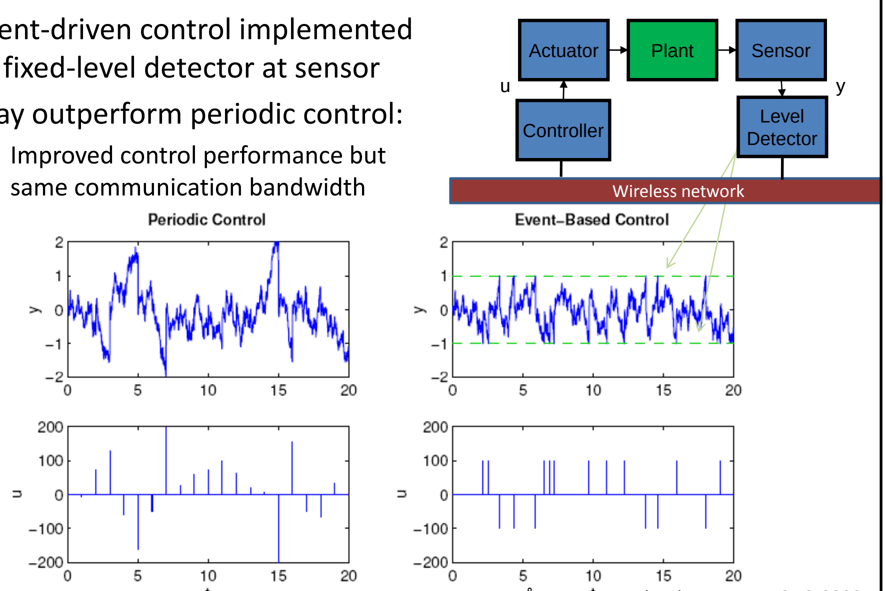
Conflict between traditional
• **control engineering:** time-driven sampling, fixed topology
and
• **networking:** event-driven communication, ad hoc topology

- Transmit information only when needed:
  - "If it ain't broken, don't fix it" [K. J. Åström]



Time- vs. event-driven control

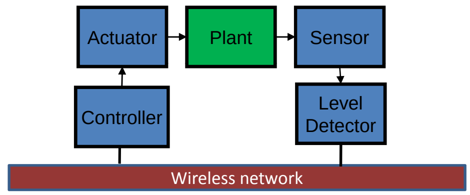
- Event-driven control implemented as fixed-level detector at sensor
- May outperform periodic control:
  - Improved control performance but same communication bandwidth



Åström & Bernhardsson, *IEEE CDC*, 2002

When to transmit?

- Simple medium access mechanism at sensor, e.g., level detector



How to control?

- Execute control law on fixed control alphabet, e.g., piecewise constant controls

Rabi et al., *IEEE CDC, 2006* Johannesson et al., *HSCC, 2007* Cervin & Henningsson, *2008* Rabi et al., *2008*

Mathematical framework

$$dx_t = f(x_t, u_t)dt + g(x_t, u_t)dB_t$$

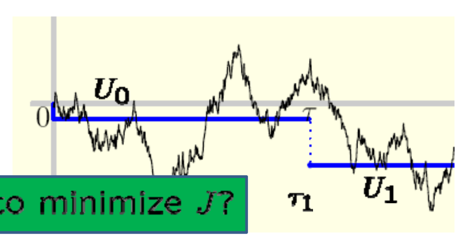
x_t state

u_t control

B_t Brownian motion

Piecewise constant controls: $u_t = \sum_{i=0}^{N} U_i \cdot \mathbf{1}_{\tau_i \le t < \tau_{i+1}}$

Cost: $J = \mathbf{E} \int_0^T L(x_s, u_s)ds$

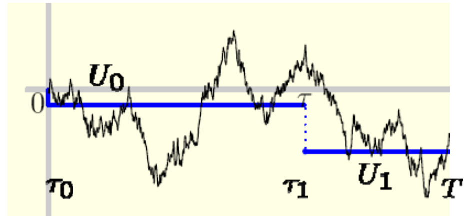


How choose $\{U_i\}$ and $\{\tau_i\}$ to minimize J?

Rabi et al., *2008*

Controlled Brownian motion with one sampling event

$$dx_t = u_t dt + dB_t$$



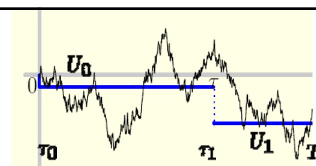
$$\min_{U_0, U_1, \tau} J = \min_{U_0, U_1, \tau} \mathbf{E} \int_0^T x_s^2 ds$$

$$= \min_{U_0, U_1, \tau} \left[\mathbf{E} \int_0^\tau x_s^2 ds + \mathbf{E} \int_\tau^T x_s^2 ds \right]$$

A joint optimal control and optimal stopping problem

$$dx_t = u_t dt + dB_t$$

$$\min_{U_0, U_1, \tau} J = \min_{U_0, U_1, \tau} \mathbf{E} \int_0^T x_s^2 ds$$



If τ chosen deterministically (not depending on x_t) and $x_0 = 0$:

$$U_0^* = 0 \qquad U_1^* = -\frac{3x_{T/2}}{T} \qquad \tau^* = T/2$$

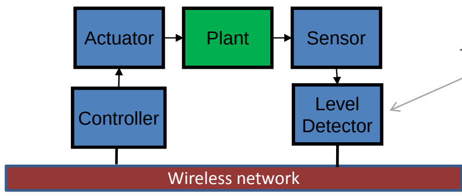
If τ is event-driven (depending on x_t) and $x_0 = 0$:

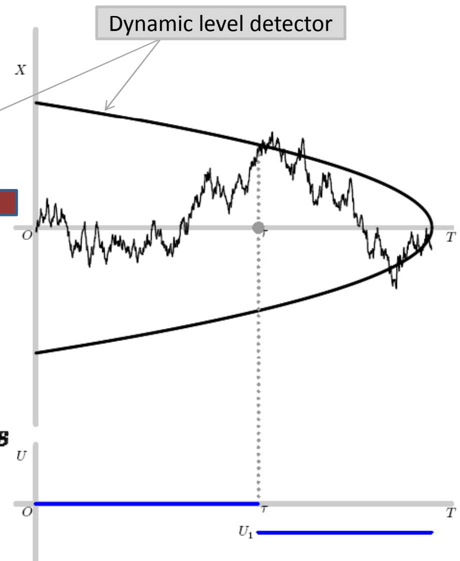
$$U_0^* = 0 \qquad U_1^* = -\frac{3x_{\tau^*}}{2(T - \tau^*)}$$

$$\tau^* = \inf\{t : x_t^2 \geq \sqrt{3}(T - t)\}$$

Envelope defines optimal level detector

Optimal level detector





$$dx_t = u_t dt + dB_t$$

$$\min_{U_0, U_1, \tau} J = \min_{U_0, U_1, \tau} \mathbf{E} \int_0^T x_s^2 ds$$

Conclusions

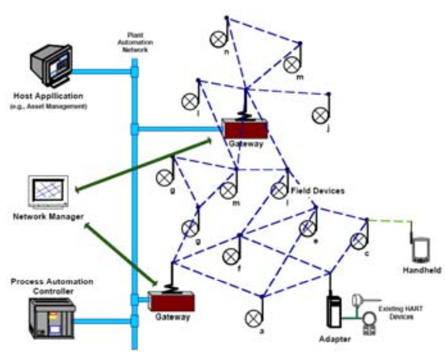
- Wide range of emerging wireless control applications

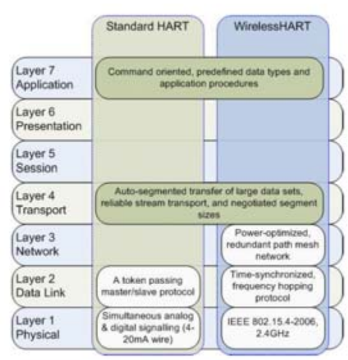
- Application constraints inspire to new theoretical problems
  - Control systems need to be robust against communication outages
- Need integrated view of control and wireless networking
  - Event-based control to support asynchronous networking

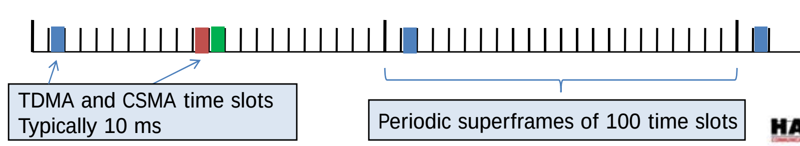
http://www.ee.kth.se/~kallej

WirelessHART

- Wireless networking protocol standard (2007) designed for control applications







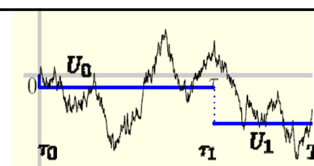
ISA SP100 Classification of Wireless Automation

Category	Class	Application	Description
Safety	0	Emergency action	*(always critical)*
Control	1	Closed loop regulatory control	*(often critical)*
	2	Closed loop supervisory control	*(usually non-critical)*
	3	Open loop control	*(human in the loop)*
Monitoring	4	Alerting	*Short-term operational consequence (e.g., event-based maintenance)*
	5	Logging and downloading/uploading	*No immediate operational consequence (e.g., history collection, sequence-of-events, preventive maintenance)*

Importance of message timeliness increases

$$dx_t = u_t dt + dB_t$$

$$\min_{U_0, U_1, \tau} J = \min_{U_0, U_1, \tau} \mathbf{E} \int_0^T x_s^2 ds$$



If τ is event-driven (depending on x_t) and $x_0 \neq 0$:

$$U_1^* = -\frac{3x_{\tau^*}}{2(T-\tau^*)}$$

- Requires numerical solution for the **Snell envelope** for given U_0
- Envelopes define level detectors