Analysis and Simulation of Embedded Control Performance using Jitterbug and TrueTime

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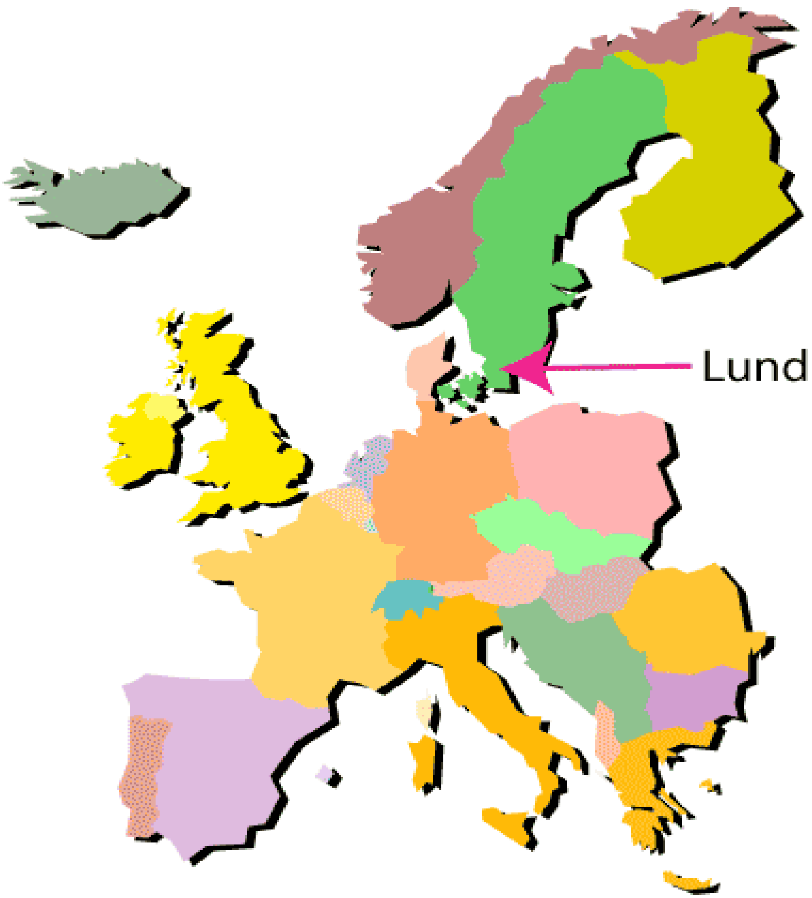
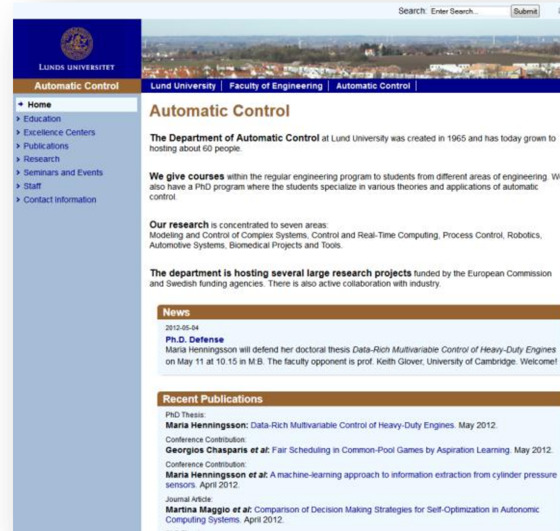


Founded in 1666

One of the largest institutes for higher education and research in Scandinavia with about 35 000 students

Department of Automatic Control

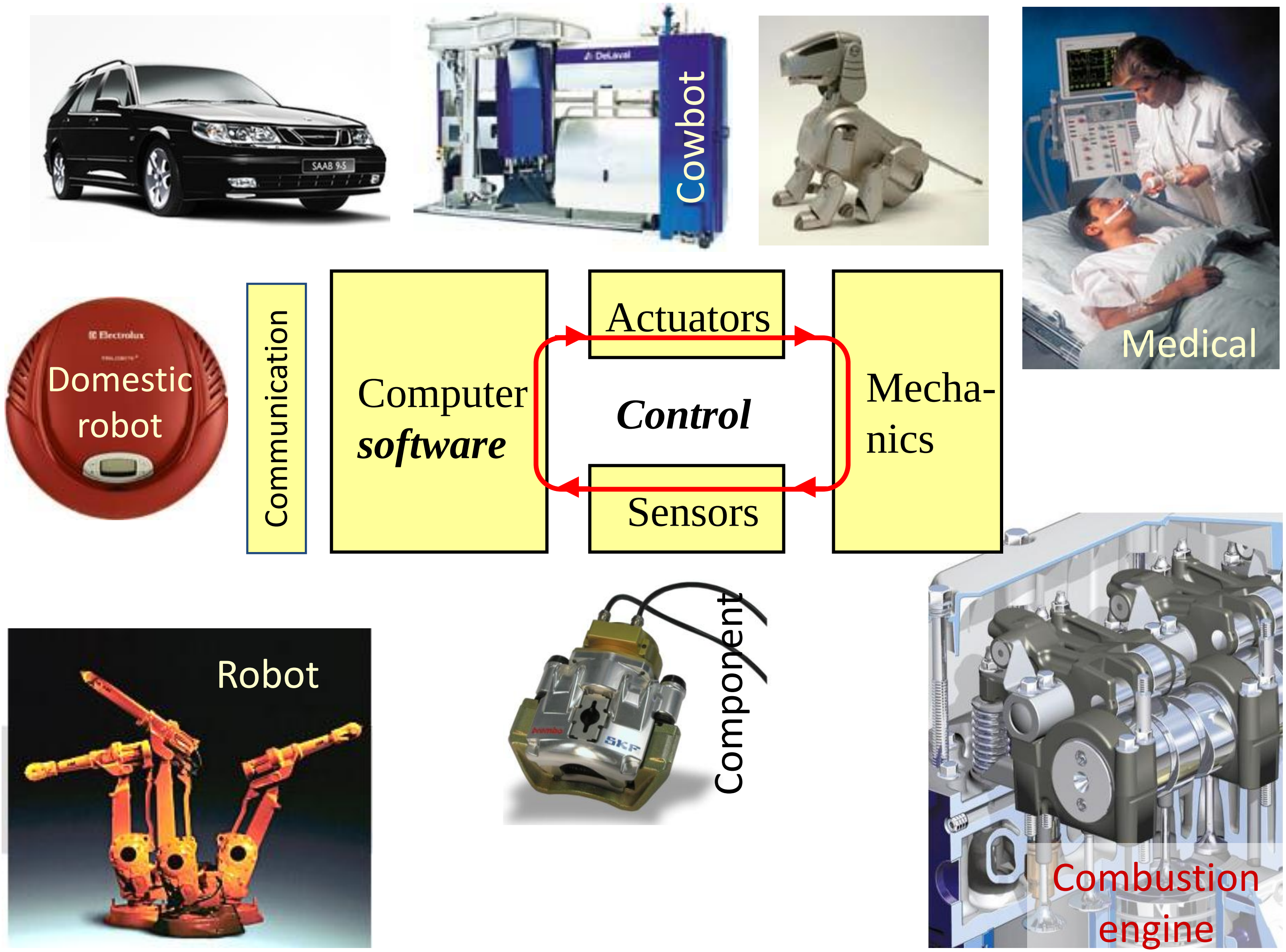
- One of the largest control departments in Europe
- Founded by Prof Karl Johan Åström
- Currently:
  - 10 Faculty
  - 34 PhD students
- Research areas:
  - Modeling and Control of Complex Systems
  - Control and Real-Time Computing
  - Process Control
  - Robotics
  - Automotive Systems
  - Biomedical Projects
  - Tools
- www.control.lth.se



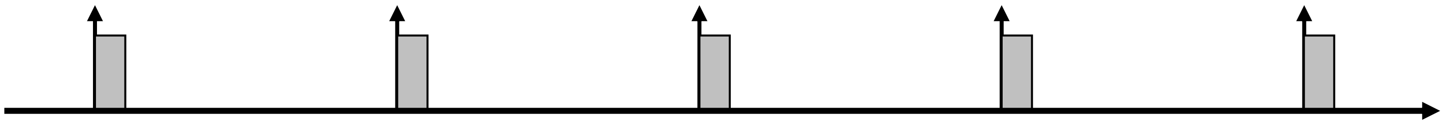
Contents

- **Networked Embedded Control**
- Stability Margin
- Average-case stochastic performance analysis using Jitterbug
- Simulation using TrueTime
- TrueTime in Modelica

Products relying on embedded control

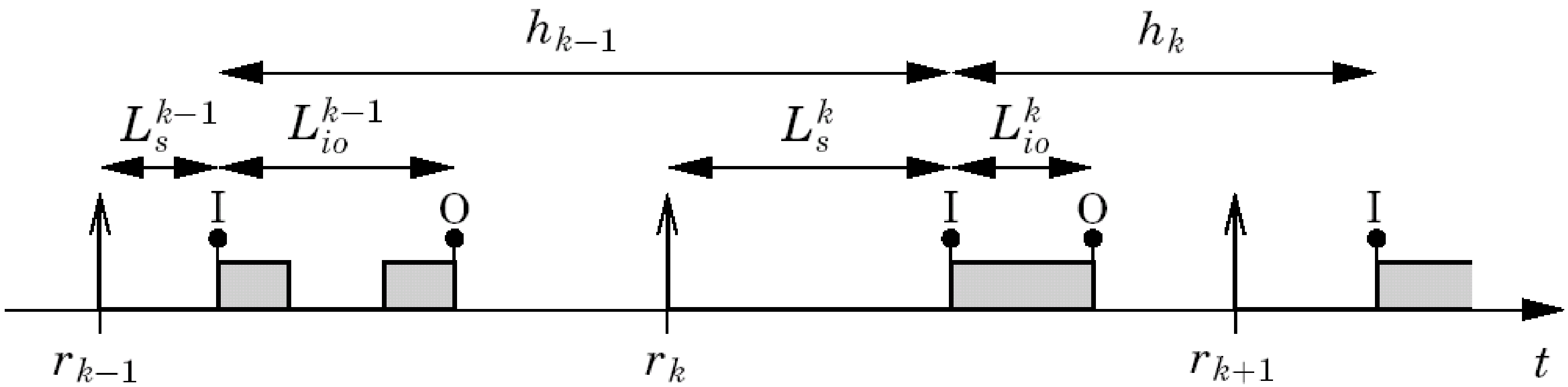


Control Loop Timing



- Classical control assumes deterministic sampling
  - in most cases periodic
  - too long sampling interval or too much jitter give poor performance or instability
- Classical control assumes negligible or constant input-output latencies
  - if the latency is small compared to the sampling interval it can be ignored
  - if the latency is constant it can be included in the control design
  - too long latency or too much jitter give poor performance or instability

Networked Embedded Control Timing



- Embedded control often implies temporal non-determinism
  - [illegible]
  - [illegible] on-deterministic kernel primitives, ...

How does this effect performance?

- Networked control often implies temporal non-determinism
  - network interface delay, queuing delay, transmission delay, propagation delay, link layer resending delay, transport layer ACK delay, ...
  - lost packets

Analysis of Control Performance

- Constant delays in linear systems --- straightforward
- Sampling jitter and input-output jitter -- more difficult
  - Worst-case stability analysis
    - Requires minimum and maximum values for the jitter
    - Stability margin theorems by Kao & Lincoln and by Cervin
  - Average-case stochastic performance analysis
    - Requires a stichastic model of latencies
    - Jitterbug toolbox
  - Simulation
    - TrueTime toolbox

Analysis of Control Performance

The control performance depends on a number of issues:

- The dynamics of the plant that is controlled
- The controller type
- The design specifications for the controller
- The nature of the disturbances
- The delay distribution
- What type of control performance that we are interested in

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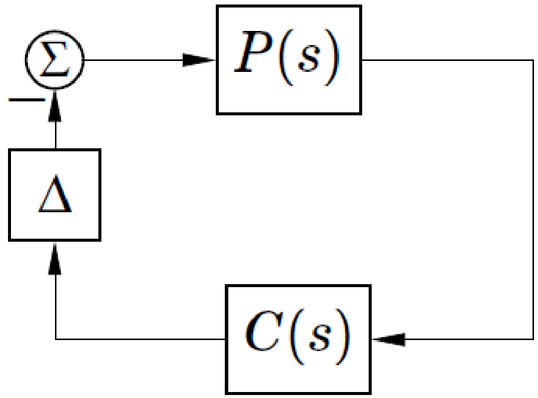
Jitter Margin – Stability under Input-Output Jitter

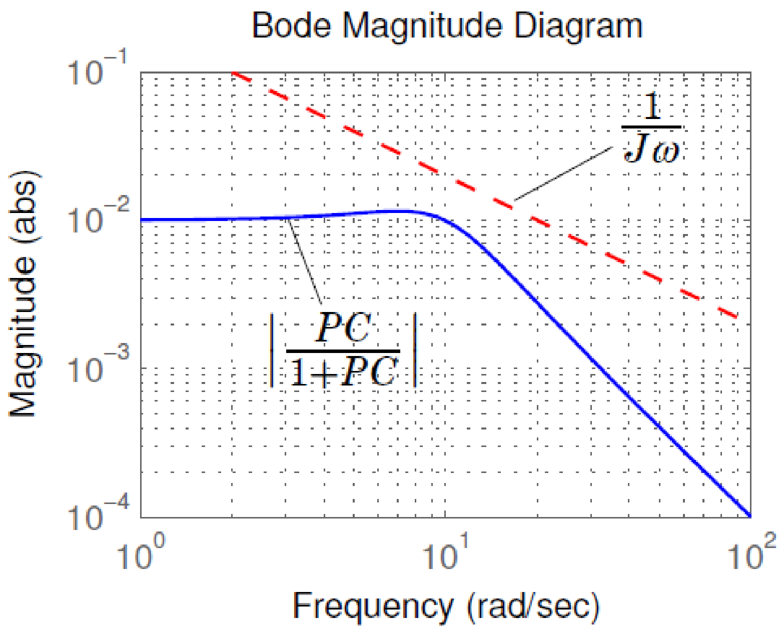
Stability theorem due to Kao and Lincoln (2004):



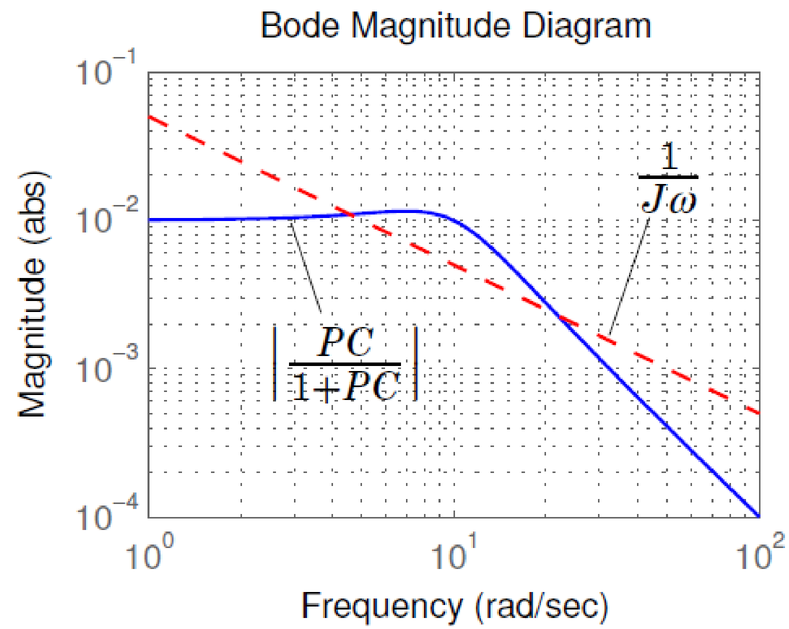
- Continuous-time plant $P(s)$
- Continuous-time controller $C(s)$
- Arbitrarily time-varying delay $\Delta \in [0, J]$
- Theorem: The closed-loop system is stable **if**

$$\left| \frac{P(i\omega)C(i\omega)}{1 + P(i\omega)C(i\omega)} \right| < \frac{1}{J\omega} \quad \forall \omega \in [0, \infty].$$

Graphical test:



Stable



Could be unstable

Stability Under Jitter – Sampled Control Case

The sampled control case is more complicated.

Assume continuous-time plant $P(s)$, discrete-time controller $C(z)$ and input-output jitter $J \leq h$.

The closed-loop system is stable if

$$\left| \frac{P_{\text{alias}}(\omega) C(e^{i\omega})}{1 + P_{\text{ZOH}}(e^{i\omega}) C(e^{i\omega})} \right| < \frac{1}{\sqrt{J} \left| e^{i\omega} - 1 \right|}, \quad \forall \omega \in [0, \pi]$$

where

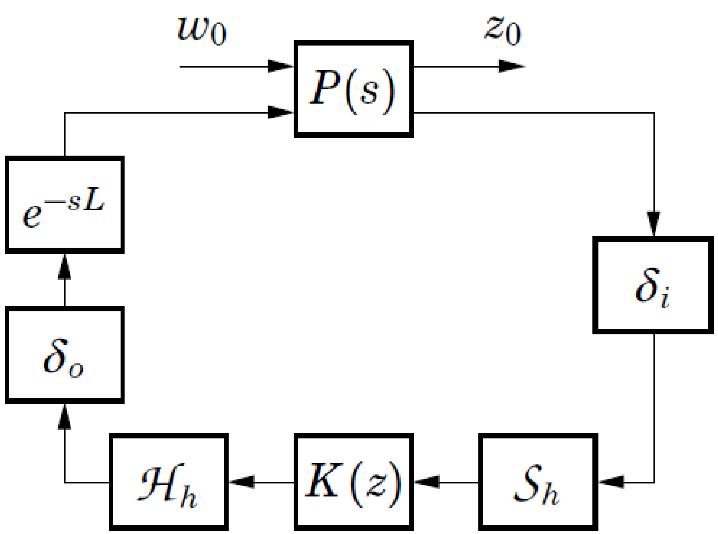
- $P_{\text{alias}}(\omega) = \sqrt{\sum_{k=-\infty}^{\infty} \left| P\left(i(\omega + 2\pi k) \frac{1}{h} \right) \right|^2}$
- $P_{\text{ZOH}}(z)$ is the ZOH-discretization of $P(s)$

Jitter Margin Limitations

- Only holds for linear systems
- Assumes zero sampling jitter
- Only uses knowledge of the minimum and maximum input-output latencies
- Does not exploit any statistical properties about the jitter

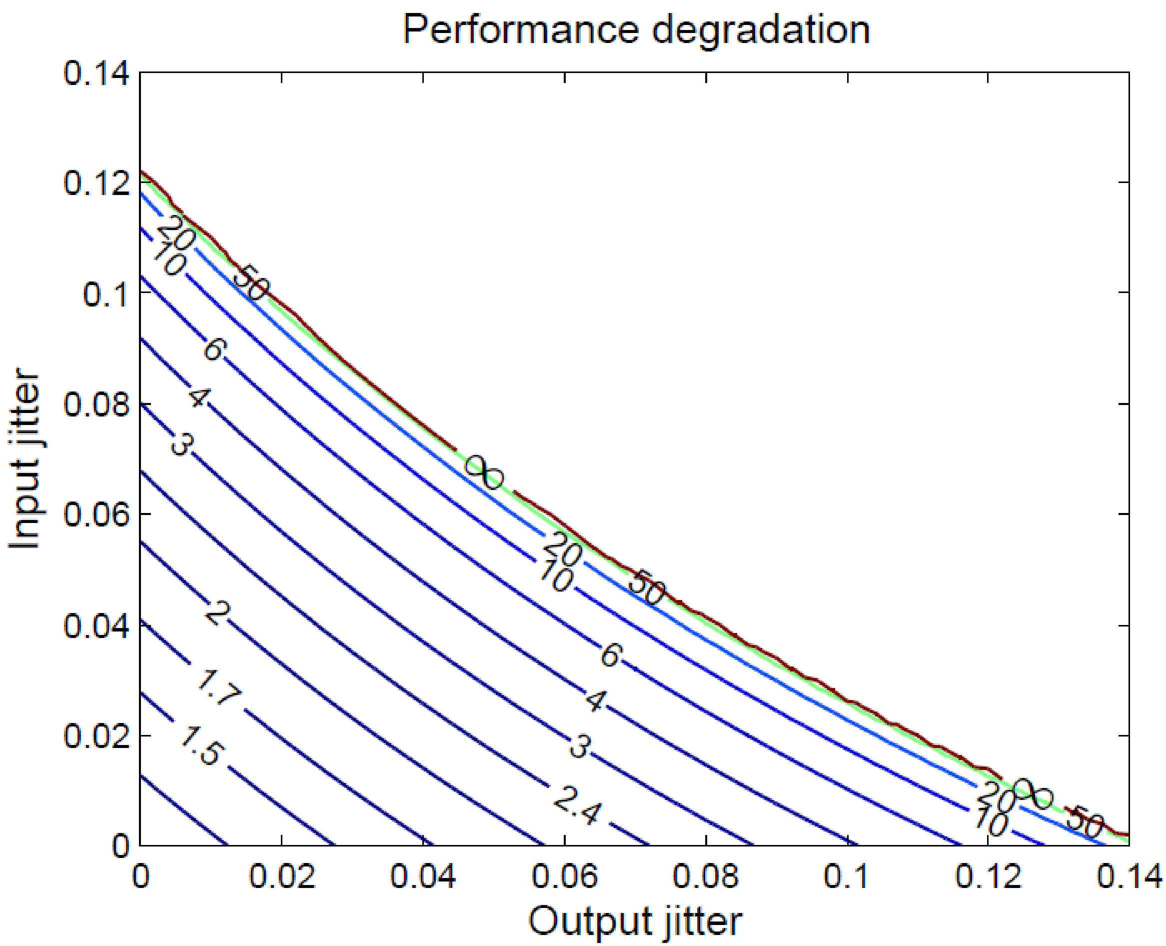
Jitter Margin for Input and Output Jitter

- Cervin (ACC 2012)



- Nominal input–output delay L
- Time-varying input delay $\delta_i(t) \in [-\frac{J_i}{2}, \frac{J_i}{2}]$
- Time-varying output delay $\delta_o(t) \in [-\frac{J_o}{2}, \frac{J_o}{2}]$
- H_∞-type performance metric: $\gamma = \sup \dfrac{\|z_0\|}{\|w_0\|}$

$$P(s) = \frac{1}{s^2 - 0.01}, \quad K(z) = \frac{-12.95z^2 + 10z}{z^2 - 0.2181z + 0.1081}, \quad h = 0.2, \quad L = 0.08$$



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Jitterbug

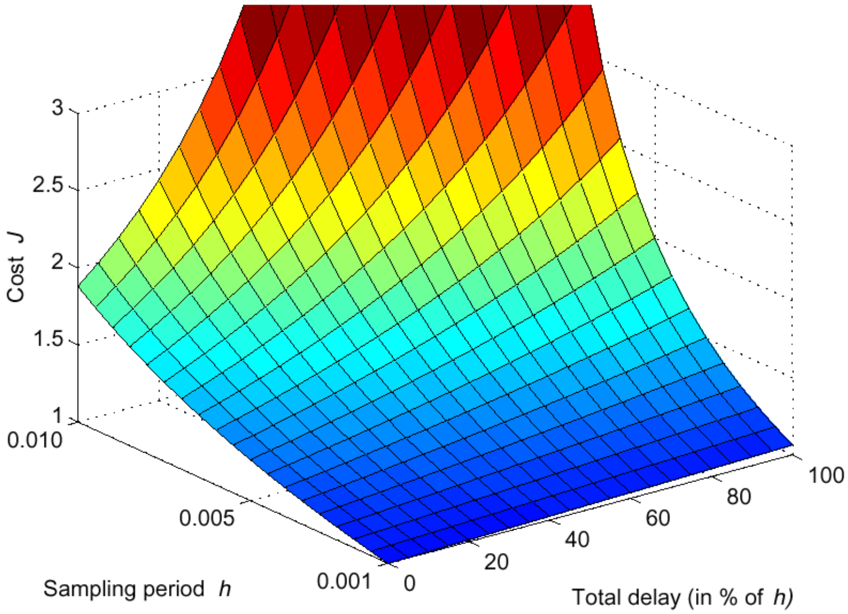
- Matlab toolbox for stochastic control analysis (Lincoln and Cervin, 2002)
- Random delays in the control loop described by probability distributions
- System disturbed by white noise
- Performance measured by quadratic cost function

$$V = \mathrm{E}\ x^T Q x$$

  - Small V $\Leftrightarrow$ good performance
  - $V = \infty$ $\Leftrightarrow$ unstable control loop

Jitterbug

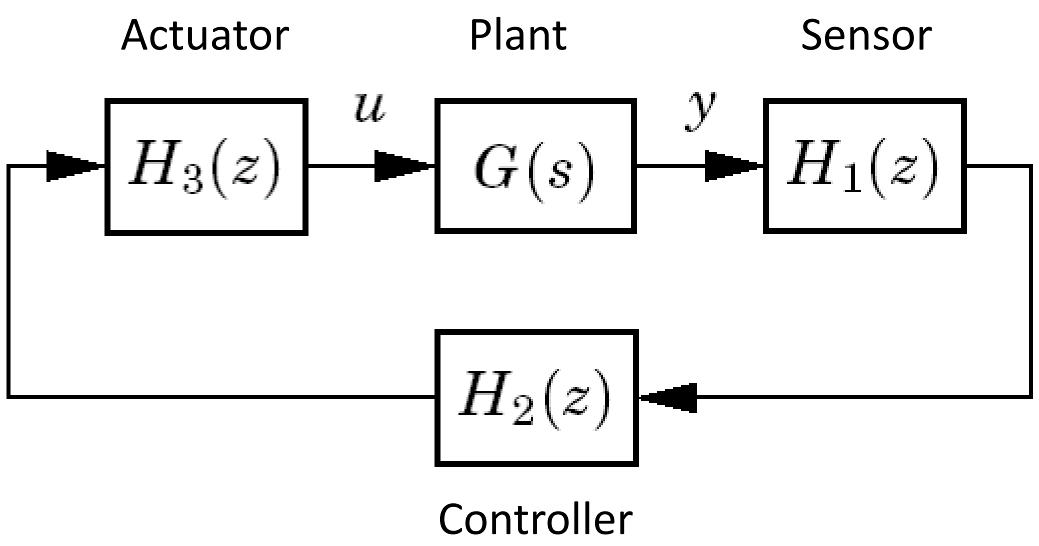
- Matlab-based toolbox for analysis of real-time control performance
- Evaluate effects of latencies, jitter, lost samples, aborted computations, etc on control performance
- Analyze jitter-compensating controllers, aperiodic controllers, multi-rate controllers
- Calculation of a quadratic performance criterion function
- Packaging of existing theory for linear quadratic Gaussian systems and jump-linear systems



Jitterbug Analysis

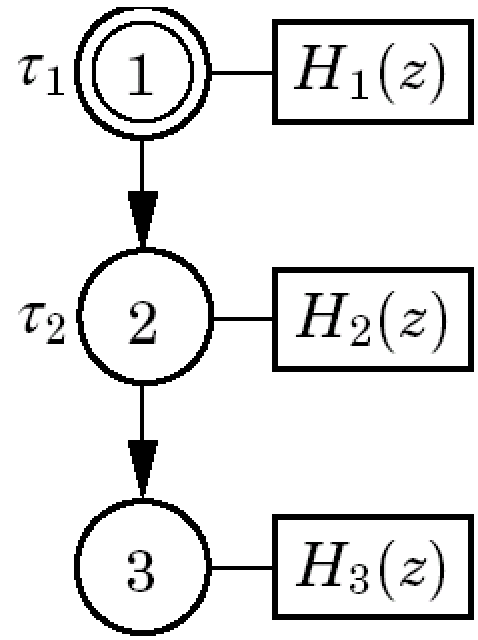
- System described using a number of connected continuous-time and discrete-time transfer function blocks driven by white noise

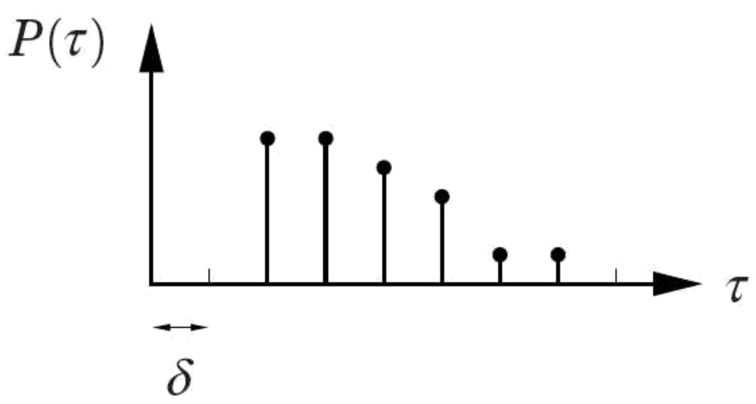
Distributed Control Loop:



Jitterbug Analysis

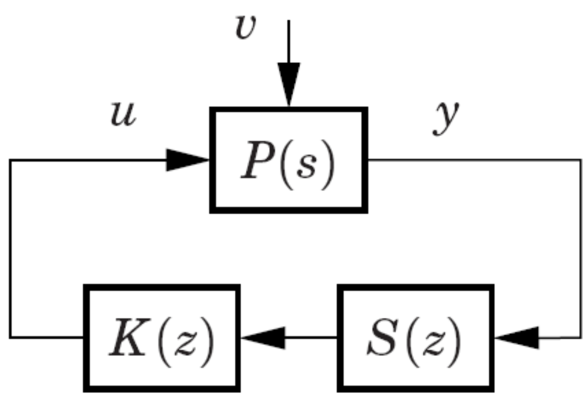
- The execution of the blocks is described by a stochastic timing model expressed as an automaton
- Each state can trigger one or more discrete systems
- Time intervals are represented by discrete probability distributions



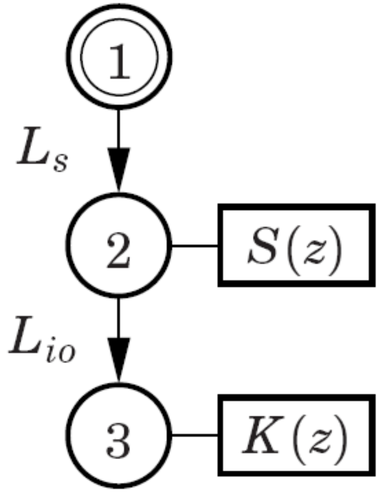


Jitterbug Model - Example

Signal model:



Timing model:



- $P(s)$ – process
- $S(z)$ – sampler
- $K(z)$ – controller/actuator

Jitterbug Example Script

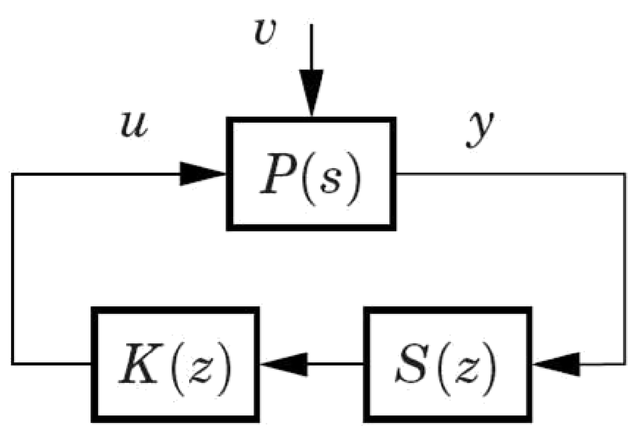
```
Ptau1 = 1; % Corresponds to zero delay
Ptau2 = [zeros(1,round(L/dt)) 1];
N = initjitterbug(dt,h);
  % timegrain dt, periodic system with period h
N = addtimingnode(N,1,Ptau1,2);
  % add timing node with delay distributin to next node
N = addtimingnode(N,2,Ptau2,3);
N = addtimingnode(N,3);
  % add timing node with no next node
```

Jitterbug example script

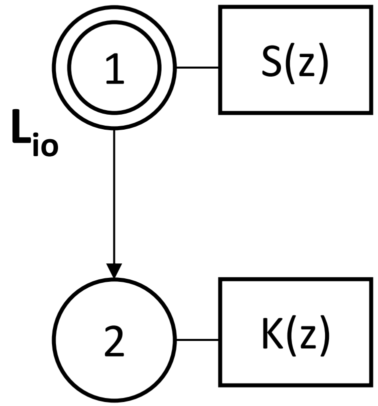
```
N = addcontsys(N,1,plant,3,Q,R1,R2);
  % add cont-time LTI system taking its input from syst 3
N = adddiscsys(N,2,1,1,2);
  % add disc-time LTI system (sampler) taking its input
  % from system 1 and executing in timing node 2
N = adddiscsys(N,3,ctrl,2,3);
  % add disc-time LTI system (controller) taking its
  % input from system 2 and executing in timing node 3
N = calcdynamics(N);
  % Calculate internal dynamics
J = calccost(N)
  % Calculate (and display) cost
```

Simple Example

Signal model:



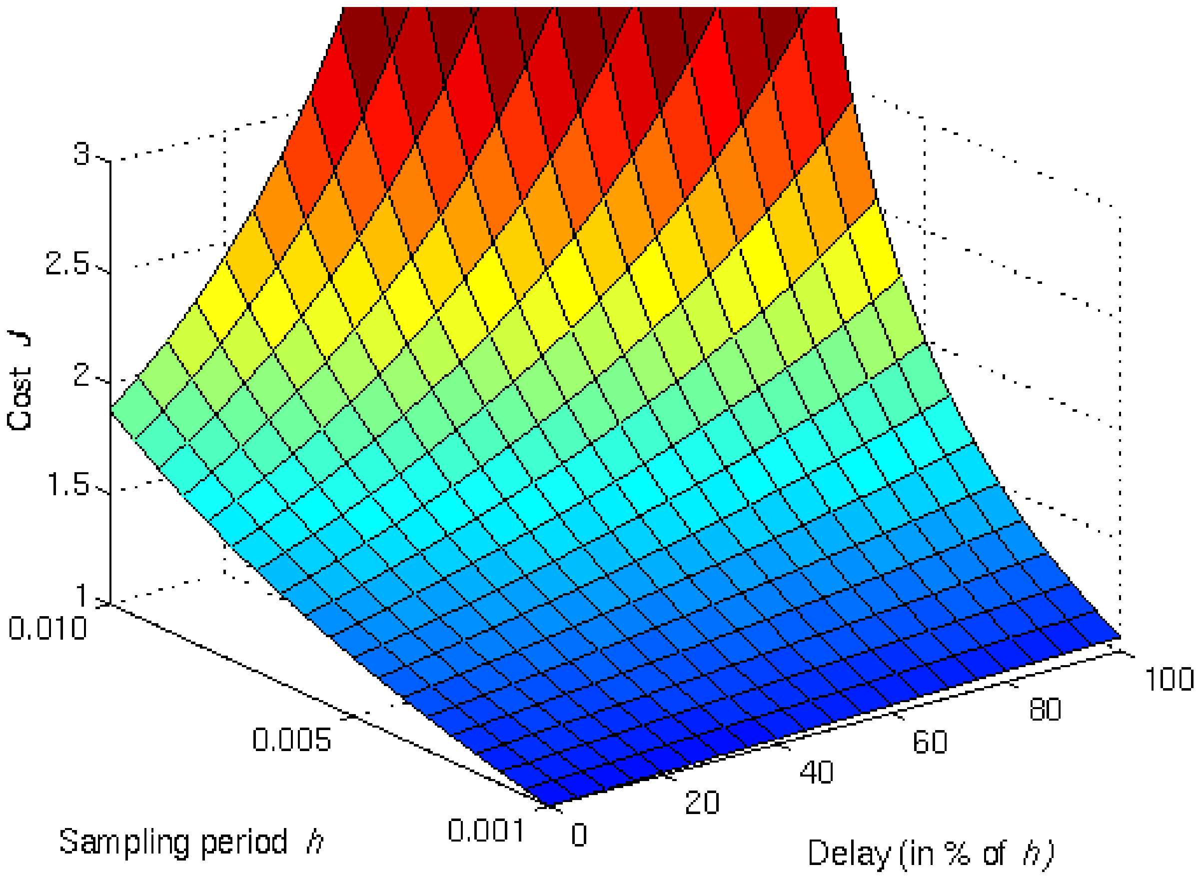
Timing model:



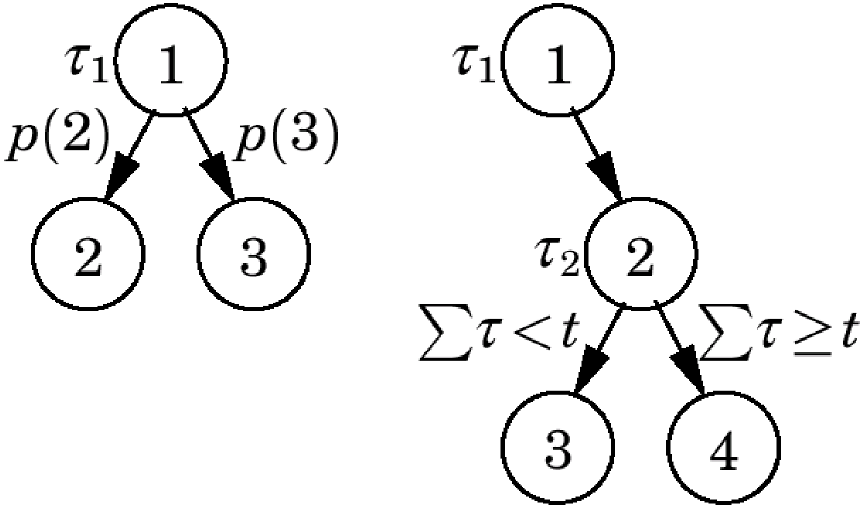
- P(s) – Process (Inverted pendulum)
- S(z) – Sampler (perfect sampling)
- K(z) – Controller + actuator
- L_{io} – input output latency

Demo

Results


3
2.5
2
1.5
1
Cost J
0.010
0.005
0.001
Sampling period h
0
20
40
60
80
100
Delay (in % of h)

More complicated cases



- random choice of path
- choice of path depending on delay
- different update equations in different nodes
- aperiodic systems
- ...

Aperiodic Systems

- Jitterbug supports both periodic and aperiodic systems
- Periodic:
  - `>calccost`
  - Analytical solution, reasonably fast
- Aperiodic:
  - `>calccostiter`
  - Iterative computation with possibly very slow convergence

Internal Workings

1. Sample the continuous-time system, the noise, and the cost function with the time-grain δ
2. Translate the timing model into a Markov chain
3. Formulate the closed-loop system as a discrete-time jump linear system

$$x(k+1) = \Phi_i(k)x(k) + e(k), \qquad \mathrm{E}\{e(k)e^T(k)\} = R_i(k)$$

   where $\Phi_i(k)$ and $R_i(k)$ depends on the Markov state i

4. Compute the stationary covariance $P = \mathrm{E}\{xx^T\}$ from

$$P_i(k+1) = \mathrm{E}\{\Phi_i(k)P_i(k)\Phi_i(k)^T + R_i(k)\}$$

Computational Complexity

- A continuous-time system of order n requires n internal states
- A discrete system of order n requires $n + 1$ internal states (one extra for the output)
- The stationary covariance P can be found directly by solving a linear system of equations of dimension n^2
  - n – total number of internal states
- The amount of memory required is $n^4 2m(p + 1)$
  - m – number of timing nodes
  - p – number of time-steps per period ($= \frac{h}{\delta}$)

Pros and cons

Pros:

- Analytical performance computation
- Fast to evaluate cost for a wide range of parameters
- Guarantees stability (in mean-square sense) if cost is finite

Cons:

- Simplistic timing models
  - Indepedent delays
  - Delay distributions may not change over time
- Only linear systems and quadratic costs
- Requires knowledge about latency distributions
  - Where do we get this from?
  - Existing scheduling theory can at best give worst-and best-case values
- Statistical analysis
  - The calculated cost is an expected value
  - All results only hold in a mean-value sense
    - Not suitable as a basis for formal verification
  - Timing scenarios with probability zero are disregarded by the analysis
    - E.g. switching-induced instability

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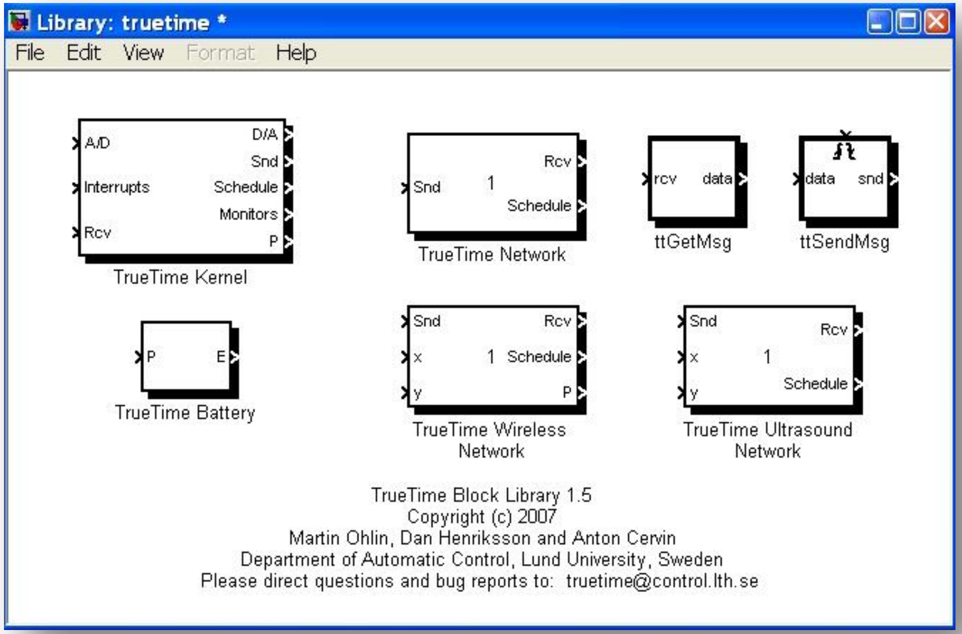
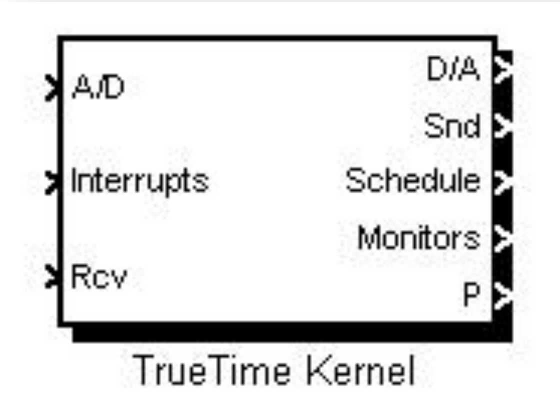
TrueTime

- Simulator for the cyber parts of CPS
- Embedded in physical system simulators (Simulink, Modelica)
- Simulation of
  - Real-time kernels
  - Wired and wireless networks
- Developed in Lund since 1999
  - Version 2.0
  - Large userbase
  - GPL



Modeling of Computations

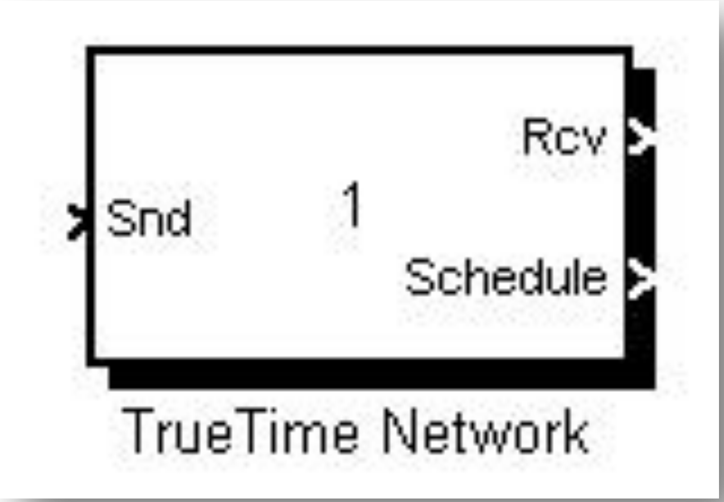
- Simulates an event-based real-time kernel
- Executes user-defined tasks and interrupt handlers
  - C/C++ or M-files
- Arbitrary user-defined scheduling policies
- Real-time primitives
- Code structured into code segments
  - emulate multithreading




```
function [exectime,data] = my_ctrl(segment,data)
switch segment,
  case 1,
     data.y = ttAnalogIn(1);
     data.u = calculate_output(data.x,data.y);
     exectime = 0.002;
  case 2,
     ttAnalogOut(1,data.u);
     data.x = update_state(data.x,data.y);
     exectime = 0.004;
   case 3,
     exectime = -1;
end
```

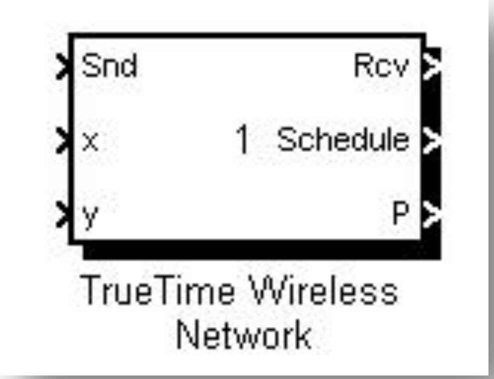
Modeling of Wired Networks

- Models the medium access delay and the transmission delay
- A number of pre-defined data-link layer protocols
  - Switched Ethernet
  - CAN
  - Round Robin
  - FDMA
  - TDMA
  - CSMA/CD (Shared Ethernet)
  - Flexray
  - PROFINET IO

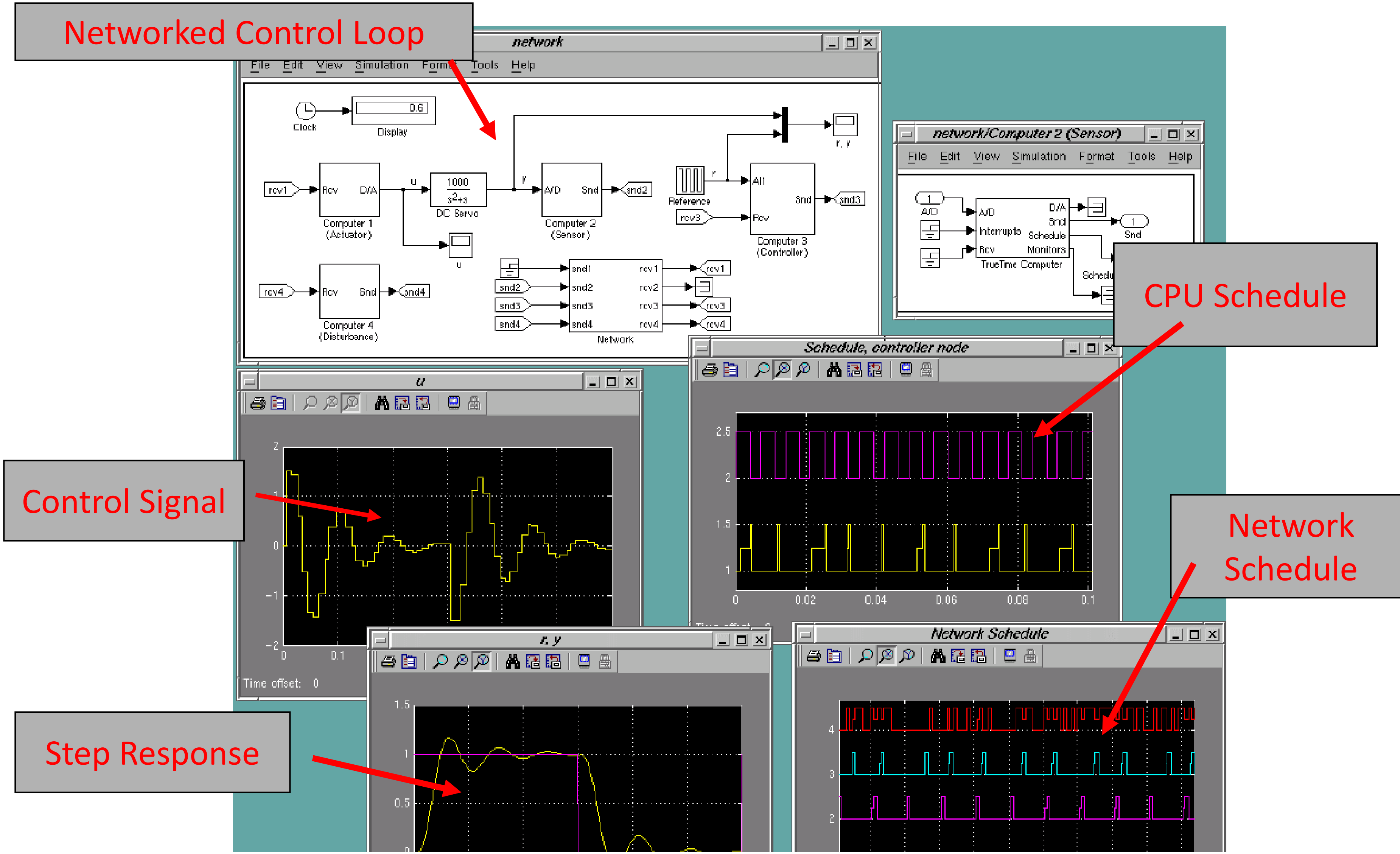


Modeling of Wireless Networks

- Supports two common MAC layer policies:
  - IEEE 802.11 b/g (WLAN)
  - IEEE 802.15.4 (“ZigBee”)
  - (Wireless HART - implemented by ABB)
- x and y inputs for node locations (2D)
- Radio models:
  - Exponential path loss (default)
  - User-defined models to model multi-path propagation, fading etc

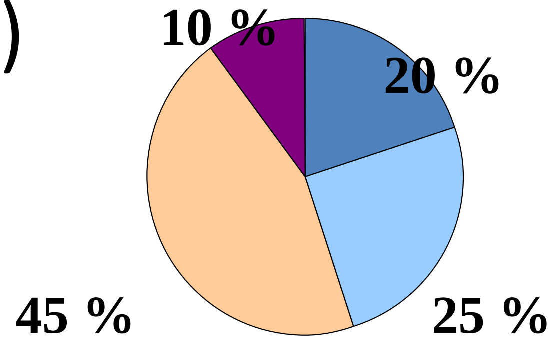


TrueTime: Networked Embedded Control

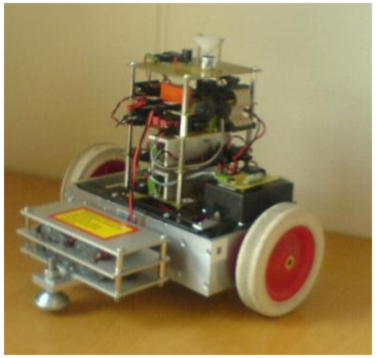


New Features

- Multicore kernels
  - Each TrueTime kernel may have multiple cores
  - Partitioned scheduling
  - `ttSetNumberOfCPUs(no)`
  - `ttSetCPUAffinity(task,cpu)`
- Constant bandwidth servers (CBS)
  - Virtual processors
  - Temporal isolation
  - `ttCreateCBS(budget,period)`
  - `ttAttachCBS(task,CBS)`
  - `ttSetCBSParameters(budget, period)`



TrueTime: Mobile Robotics



- Tunnel road safety scenario in RUNES
  - EU FP6 IP (2004-2007)
  - Coordinated by Ericsson
- Stationary sensor network in a road tunnel

- Mobile robots as mobile gateways for restoring connectivity among isolated subislands of the network

Localization

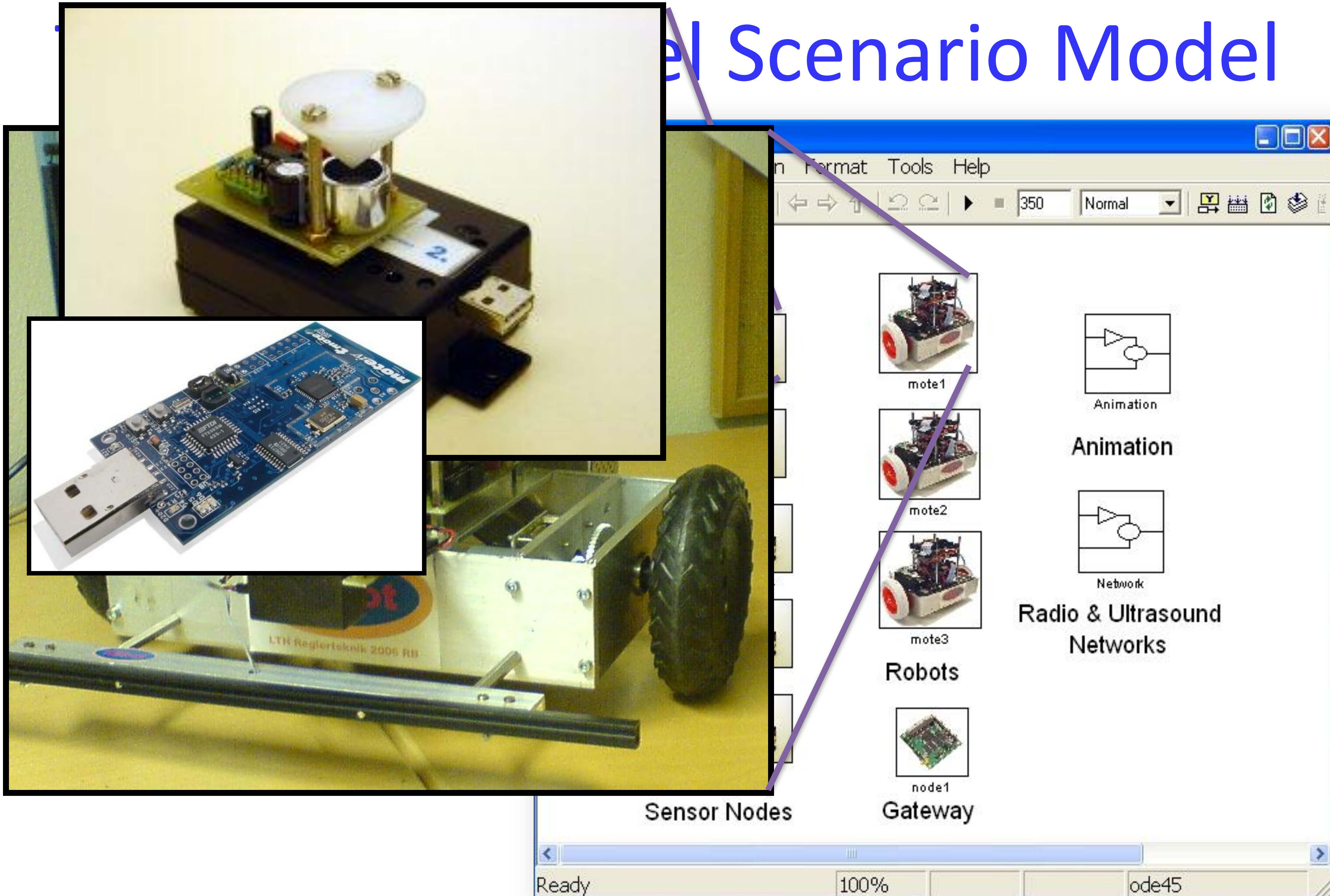
- Ultrasound-based
  - Active mobile robots
  - Passive stationary nodes
- Robot broadcasts radio packet and ultrasound pulse ”simultaneously”
- Difference in time-of-arrival allows each reachable node to calculate its distance to the robot
- Each node sends its distance measurement back to the robot
- Extended Kalman Filter fuses distance measurements with wheel encoders

Verification Problem

- Robot with several microprocessors, I2C bus communication
- Sensor network radio communication
  - IEEE 802.11 b/g (WLAN)
  - AODV routing protocol
- Ultrasound localization
- IR-based obstacle avoidance
- Control and estimation

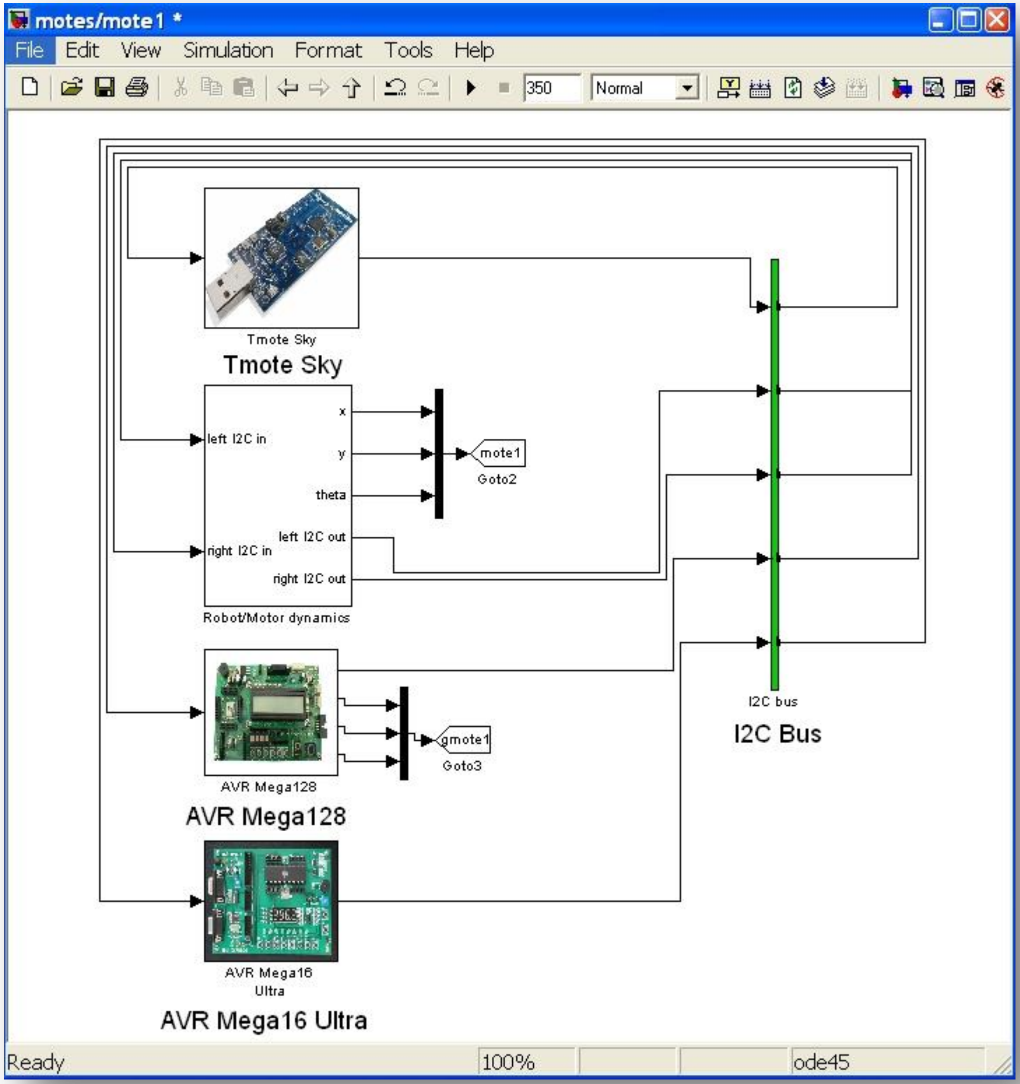
➡ How verify the functionality and timeliness of this??
  - TrueTime used for developing a simulator in parallel with the real physical implementation
  - Proof of concept and verification

el Scenario Model

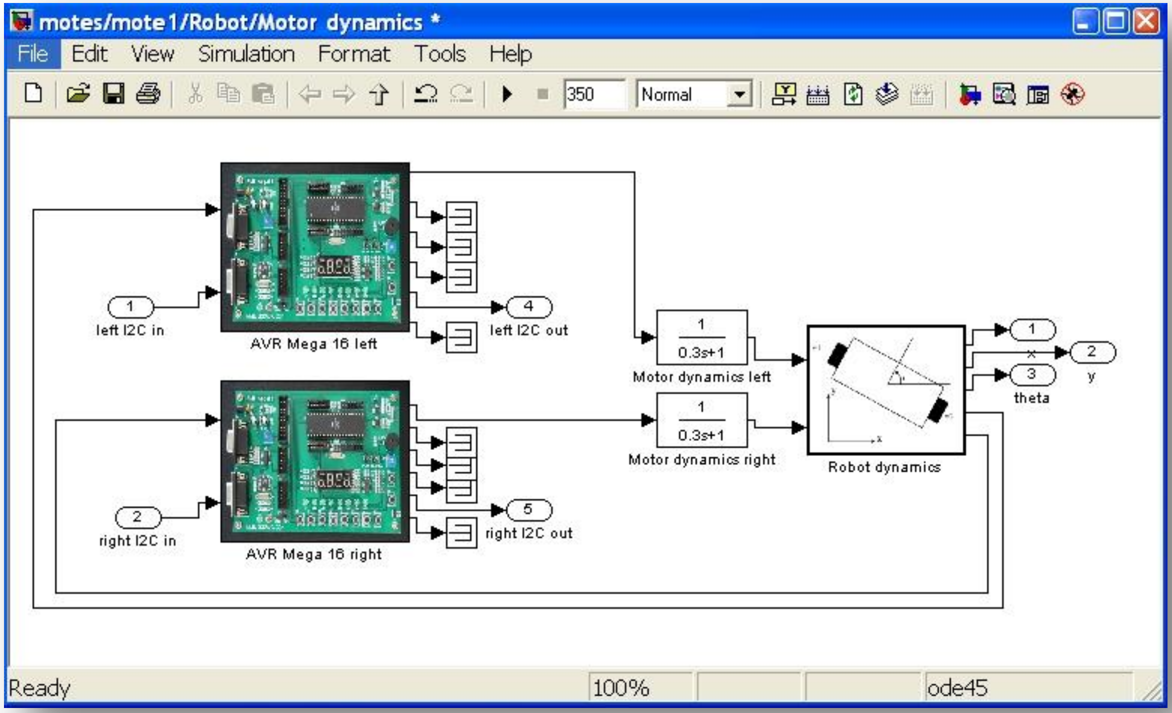


Robot Submodel

- Tmote Sky
  - Radio interface & bus master
  - Robot controller
- AVR Mega128
  - Compute engine
  - IR interface
  - EKF, navigation, and obstacle avoidance
- AVR Mega16
  - Ultrasound interface
- I2C bus
- Wheel and motor submodel

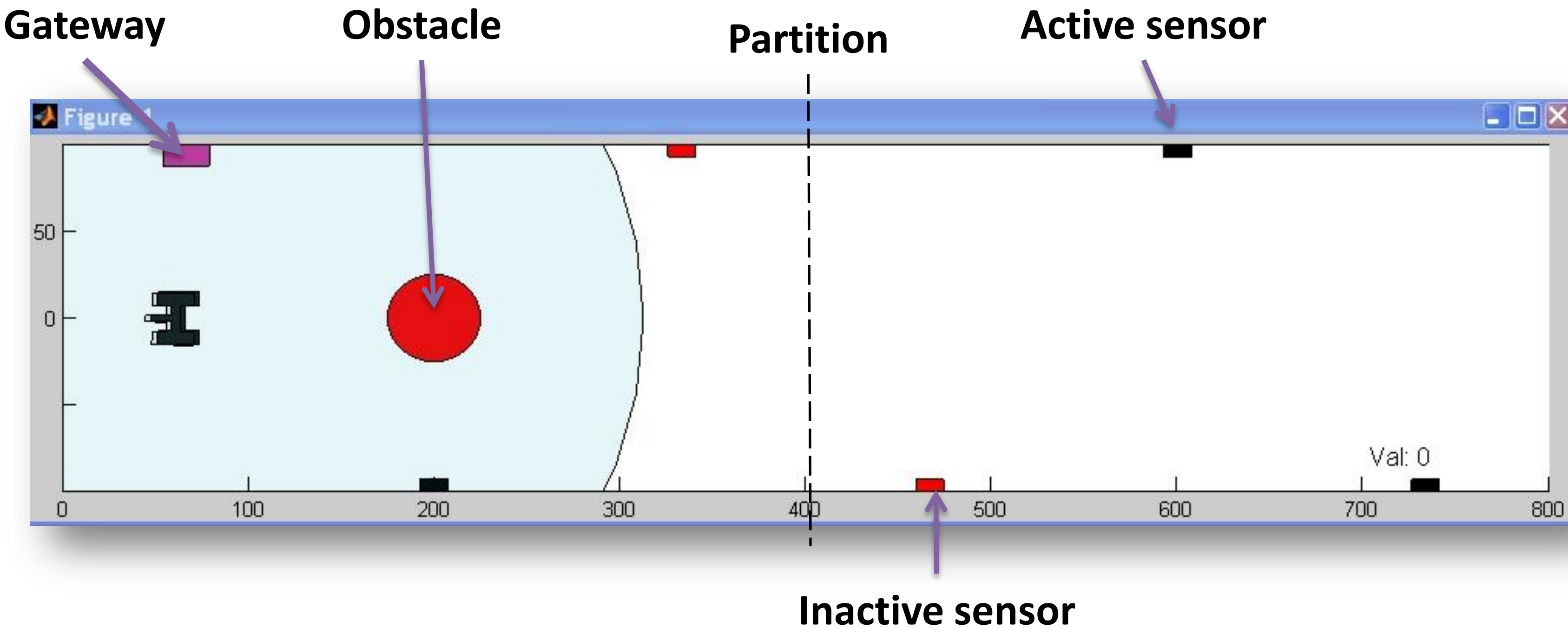


Wheel and Motor Submodel



- One AVR Mega16 for each wheel/motor
- Simple motor models
- Dual-drive unicycle robot dynamics model

Animation



- Both the true position of the robots and their internal estimate of their position are shown
- A sensor node that is turned off will not participate in the message routing and in the ultrasound localization

Demo

Video Demo

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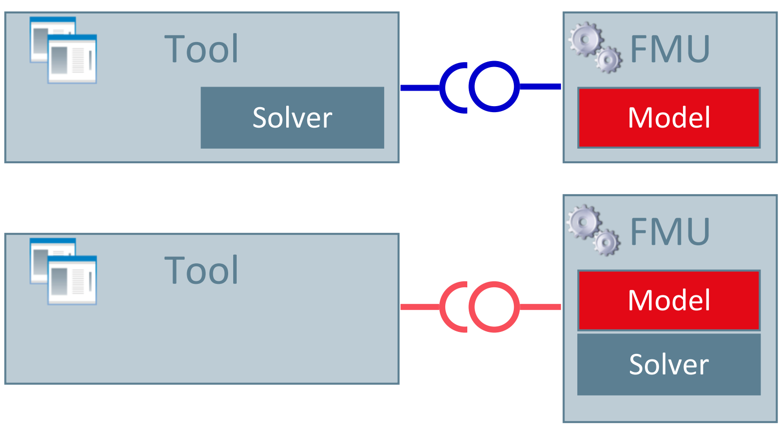
TrueTime for Simulink

- S-function interface
  - Kernels
  - Networks
- Task code
  - C/C++
  - M-file script language

TrueTime for Modelica

- Network part
  - Native Modelica version available
  - External C code version for Dymola available
- Full TrueTime
  - Flexible Mockup Interface (FMI)
    - Open source non-proprietary model exchange format
    - Model Exchange
    - Co-Simulation



TrueTime for FMI

- Kernels and Networks are Flexible Mockup Units (FMUs)
  - Modelica simulation tools:
    - Dymola
    - Open-source tools: OpenModelica, JModelica
  - Non-Modelica tools that embrace FMI
- Task code written in C
- Work in progress
  - Vanderbilt University
  - DARPA Adaptive Vehicle Make (AVM) programme
  - TrueTime a part of the Meta toolchain for CPS

Conclusions

- Networked embedded control often implies temporal nondeterminism
- New tools are needed to simplify the design space exploration
- Three examples:
  - Jitter margin – worst-case stability results
  - Jitterbug – average-case stochastic performance analysis
  - TrueTime – simulation of real-time kernels and networks
- Available through www.control.lth.se