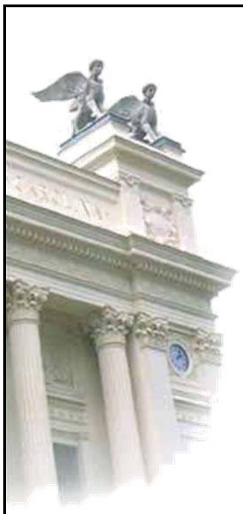

Simulation of Cyber-Physical Control Systems

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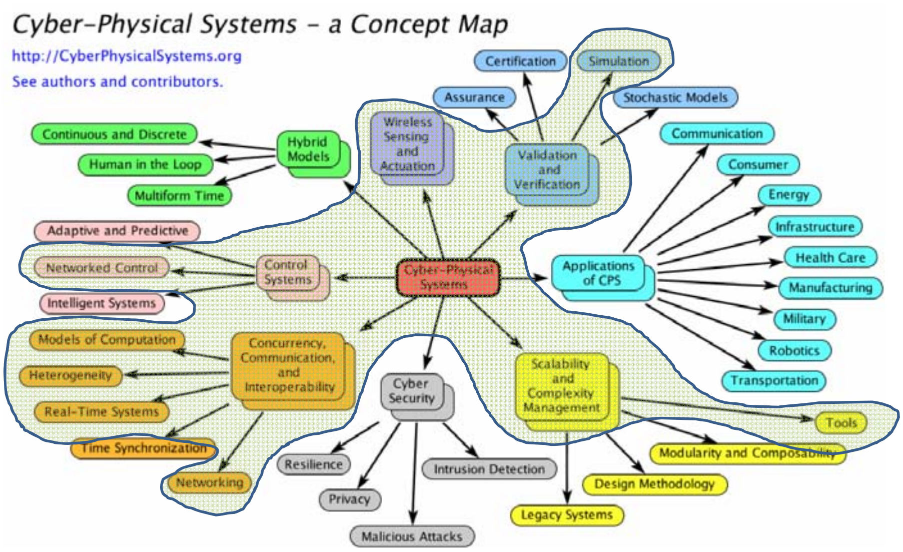
Notre Dame Workshop on Control of Cyber-Physical Systems, London, Oct 20-21, 2012

Contents

- Simulation of CPS
- TrueTime
  - New features
- Truetime in Simulink
  - Mobile robotics demo
- Truetime in Modelica
  - Demo

CPS Taxonomy



CPS and Control

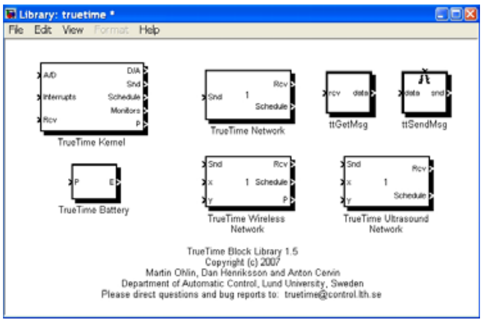
- Large-scale distributed and decentralized control
  - Large scale
  - Decentralized analysis, synthesis and optimization
  - Utilize sparsity
- Resource-constrained implementation platforms
  - Embedded and networked control
  - Temporal nondeterminism and temporal robustness
  - Delays, jitter, lost packets, quantization, ….
  - Codesign, cross/layer design, …..

Simulation of CPS

- Complement to formal methods
- When formal methods are not applicable
- Need simulation tools to cover both the cyber part and and the physical part
- Holistic co-simulation of
  - computations inside the computers
    - tasks and interrupt handlers
  - wireless and wired communication
  - dynamics of the physical parts
  - sensor and actuator dynamics
  - the power consumption in the nodes

TrueTime

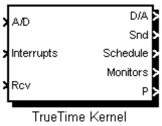
- Simulator for the cyber parts of CPS
- Embedded in physical system simulators (Simulink, Modelica)
- Simulation of
  - Real-time kernels
  - Wired and wireless networks
- Developed in Lund since 1999
  - Version 2.0
  - Large userbase
  - GPL

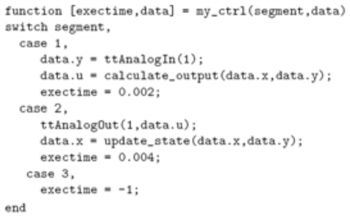


TrueTime Block Library 1.5
Copyright (c) 2007
Martin Ohlin, Dan Henriksson and Anton Cervin
Department of Automatic Control, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

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

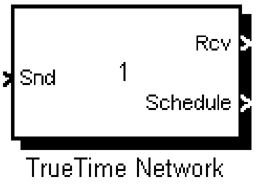




```
function [exectime,data] = my_ctrl(segment,data)
switch segment,
  case 1,
     data.y = ttAnalogIn(1);
     data.u = calculate_output(data.x,data.y);
     exectime = 0.002;
  case 2,
     ttAnalogOut(1,data.u);
     data.x = update_state(data.x,data.y);
     exectime = 0.004;
   case 3,
     exectime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

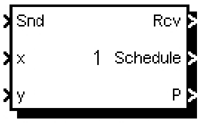
Modeling of Wired Networks

- 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”)
- x and y inputs for node locations (2D)
- Radio models:
  - Exponential path loss (default)
  - User-defined models to model fading etc

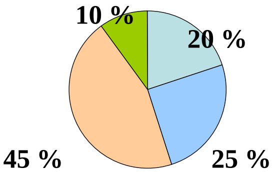


TrueTime Wireless Network

9

New Features

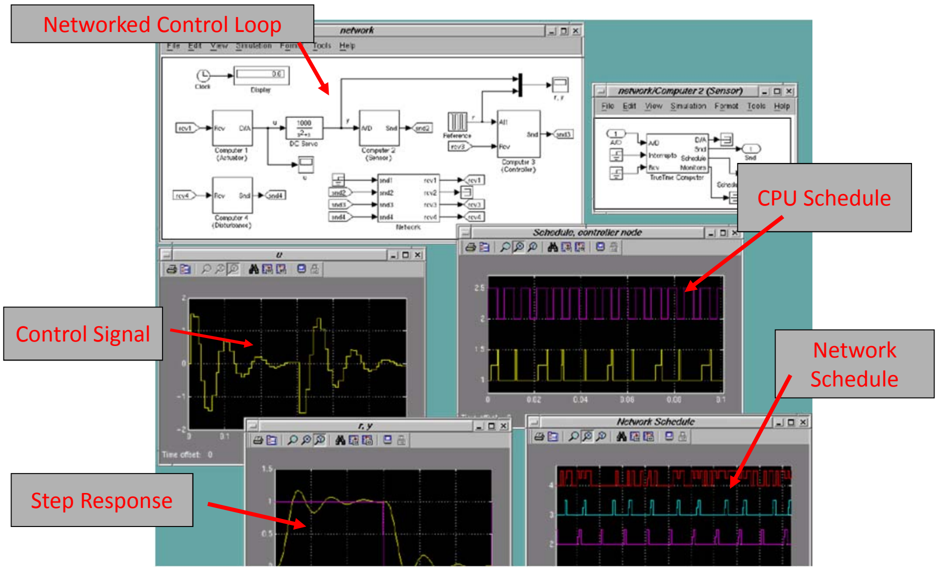
- Multicore kernels
  - Each TrueTime kernel may have multiple cores
  - Partitioned scheduling
  - `ttSetNumberOfCPUs(no)`
  - `ttSetCPUAffinity(task,cpu)`
- Constant bandwidth servers (CBS)
  - Virtual processors
  - Temporal isolation
  - `ttCreateCBS(budget,period)`
  - `ttAttachCBS(task,CBS)`
 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



TrueTime for Simulink

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

TrueTime: Networked Embedded Control



Networked Control Loop

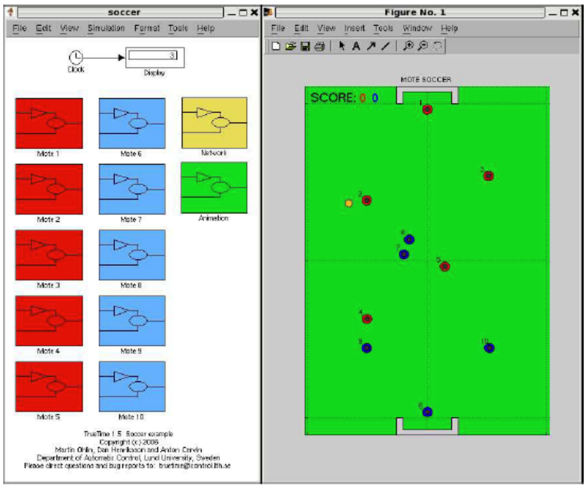
CPU Schedule

Control Signal

Network Schedule

Step Response

TrueTime: Mobile Wireless Robotics



TrueTime 1.5 Soccer example
Copyright (c) 2008
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Department of Automatic Control, Lund University, Sweden
Please direct questions and bug reports to: truetime@control.lth.se

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

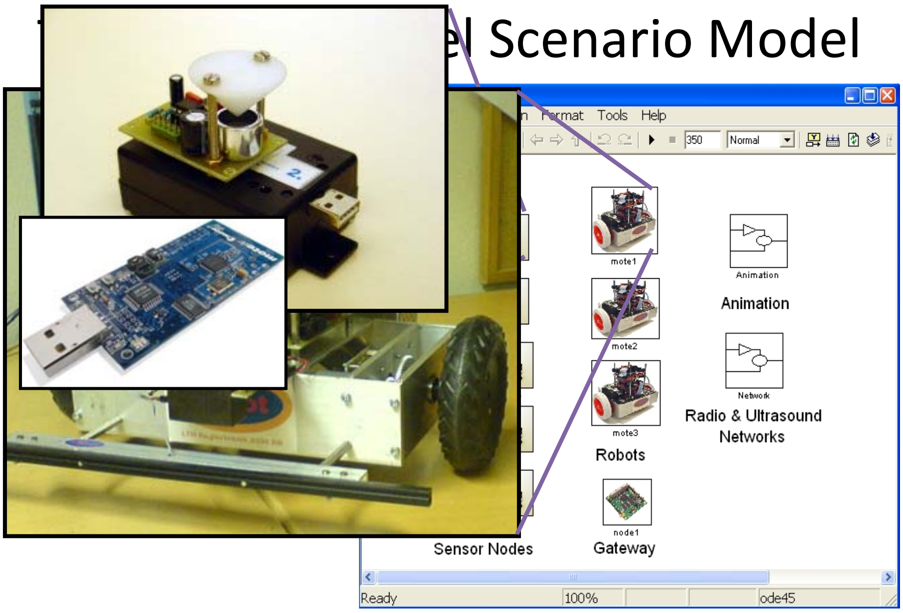
- Ultrasound-based
  - Active mobile robots
  - Passive stationary nodes
- Robot broadcasts radio packet and ultrasound pulse ”simultaneously”
- Difference in time-of-arrival allows each reachable node to calculate its distance to the robot
- Each node sends its distance measurement back to the robot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

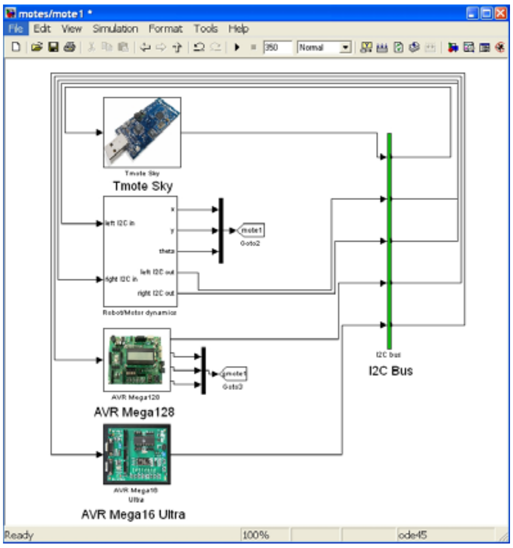
➡ How verify the functionality and timeliness of this??
  - TrueTime used for developing a simulator in parallel with the real physical implementation
  - Proof of concept and verification

l Scenario Model

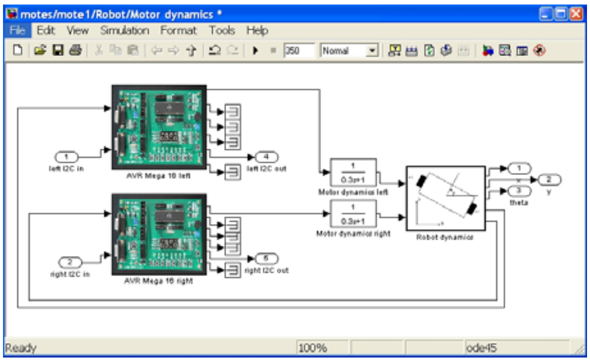


Robot Submodel

- 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

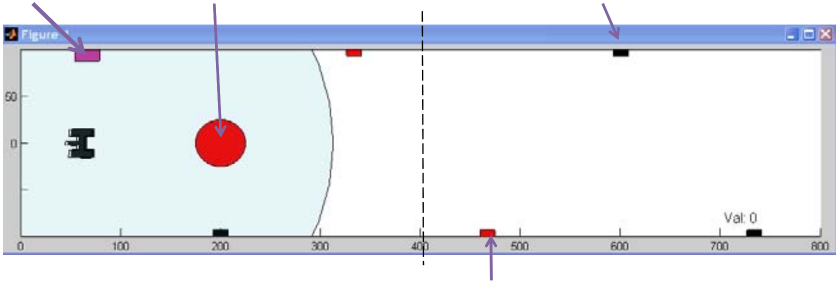


Wheel and Motor Submodel



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

Animation



Gateway

Obstacle

Partition

Active sensor

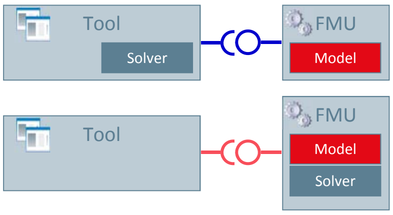
Inactive sensor

- 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

TrueTime for Modelica

- Network part
  - Native Modelica version
  - External C code version for Dymola
- 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

Demo

Simulation of CPS

- Even more important than in conventional control
- Co-simulation of cyber parts and physical parts
- TrueTime embeds models of the cyber parts within physical system simulators
  - Simulink
  - Modelica simulators

References

- Anton Cervin, Dan Henriksson, Bo Lincoln, Johan Eker, Karl-Erik Årzén, How Does Control Timing Affect Performance? Analysis and Simulation of Timing Using Jitterbug and TrueTime, *IEEE Control Systems Magazine,* **23:**3, pp. 16–30, June 2003.
- Karl-Erik Årzén, Martin Ohlin, Anton Cervin, Peter Alriksson, Dan Henriksson, Holistic Simulation of Mobile Robot and Sensor Network Applications Using TrueTime, In *Proceedings of the European Control Conference*, Kos, Greece, July 2007.
- Johan Åkesson, Karl-Erik Årzén, Magnus Gäfvert, Tove Bergdahl, Hubertus Tummescheit Modeling and Optimization with Optimica and JModelica.org—Languages and Tools for Solving Large-Scale Dynamic Optimization Problem, *Computers and Chemical Engineering,* **34:**11, pp. 1737-1749, November 2010.