Co-design of Resource-Constrained Embedded Control Systems

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Co-Design

- Increasingly important due to the resource constraints
- Several levels:
  - Mechatronics
  - Hardware-software
  - **Control and computing**
  - ....
- Why control?
  - Important class of embedded systems
  - Unique possibilities to manage uncertainty

Embedded Computing

- Increased emphasis due to the pervasive/ubiquitous computing trend
- Mass-marked products subject to hard economic constraints
- Used in un-predictable environments to a larger extent

Not a New Topic

- Control a major driving force
- In the 1960-70s constrained computer resources were a general problem that was well-known among control engineers
  - E.g. effects of fixed point calculations on control performance
- During the last 20 years a lot of old knowledge has been forgotten

Resource Constraints

- Product-level constraints ($$, size, connectability, …) generate platform-level resource constraints:
  - Computing speed
  - Memory and chip size
  - Communication bandwidth
  - Power consumption
  - …
- True in spite of the rapid development of computing hardware
- Economic constraints favor general-purpose components over special solutions

Presentation 3

Temporal Determinism

- Computer-based control theory is based on
  - equidistant sampling
  - negligible input-output latencies that can be ignored or constant latencies that easily can be compensated for
- Reality:
  - Varying execution times due to preemption, blocking, data-dependencies, caches, pipelines, network communication, …
- Result:
  - Sampling interval jitter
  - Non-negligible and varying latencies

Control Community

A new implementation and resource-aware control paradigm is needed!

Resource-Constrained Control

Soft Control Implementation Approach

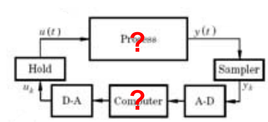
- View the temporal nondeterminism caused by the implementation platform as an uncertainty or disturbance acting on the control loop
- Use control-based approach
  - Inherent robustness of feedback
  - Design for robustness against implementation uncertainties
  - Active compensation, cp feedforward from measurable disturbances and adaptive control

Hard Control Implementation Approach

- Strive to maximize the temporal determinism
- E.g. using time-triggered and synchronous programming models
- Pros:
  - Simplifies attempts at formal verification for, e.g. safety-critical applications
  - However, a large amount of "hard" real-time control applications are **not** safety-critical
- Cons:
  - Often requires special purpose solutions, i.e., less efficient and more expensive
  - Requires complete knowledge about resource utilization, load, ..
  - May result in under-utilized systems with possibly poor control performance

Implementation-Robust Control

A tremendous amount of theory for plant uncertainties



Very little theory for implementation platform uncertainties

Hard R-T Task Model

- Periodic/sporadic tasks with constant period, hard deadline, and known WCET
- Just a model:
  - Does not fit all control problems
    - E.g. hybrid controllers, event-based controllers
  - Overly restrictive for most control problems
    - a missed deadline no catastrophy
    - a late control signal is better than no signal at all

Implementation-Robust Control

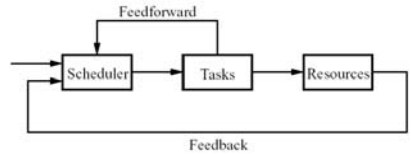
1. Temporal robustness
   - timing variations
   - Theory that allows us to decide which level of temporal determinims that a given control loop really requires in order to meet given objectives on stability and performance
     - Is it necessary to use a time-triggered approach or will an event-triggered approach do?
     - How large jitter in sampling interval and i-o latency can be tolerated?
     - Is it Ok to now and then skip a sample?
     - …..
2. Functional robustness
   - Fault-tolerance towards computer-level faults leading to data errors
   - An increasing problem in future deep sub-micron technology hardware

Resource Allocation as a Control Problem

- In an applications with multiple (control) tasks the dynamic allocation of resources to the tasks can be viewed as a control problem in itself!
- The control performance can be viewed as a quality-of-service attribute (Quality-of-Control)

Presentation 4

Feedback Scheduling Structures

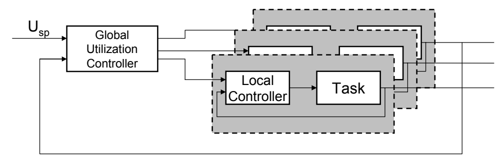


- Feedback
  - Reactive
- Feedforward
  - Proactive
  - Mode changes and admission control

Control in Real-Time Computing

- Use of control-based approaches for uncertainty management in large real-time computer and communication systems is receiving increased attention
- The worst-case approach no longer feasible
- Feedback, feedforward, ...
- Control-oriented models capturing dynamics

Feedback Scheduling Structures



- Cascaded/Layered Structure:
  - Global utilization controller that outputs the desired utilization share for each task
  - Local controllers that adjust the task parameters accordingly
  - Combine with reservation-based scheduling to provide temporal protection, cp the Control Server Model (next presentation)

Feedback Scheduling

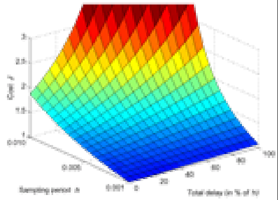
- Dynamic on-line allocation of computing resources
- Feedback from actual resource utilization
- In principle, any computing resource
- Here,
  - Scheduling of the execution of real-time tasks
  - In particular, real-time controller tasks

Tools

- New types of tools needed that take implementation-level timing effects and constraints into account
- Analysis, simulation, synthesis
- Beginning to emerge, e.g.
  - Jitterbug for analysis
  - TrueTime for simulation
- No synthesis tools yet
  - Lack of theory

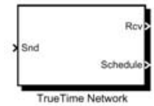
Jitterbug

- Matlab-based toolbox for analysis of real-time control performance
- Calculation of a quadratic performance criterion function
- Stochastic timing description
- Evaluate effects of latencies, jitter, lost samples, aborted computations, etc on control performance
- Analyze jitter-compensating controllers, aperiodic controllers, multi-rate controllers, …..



Network Block

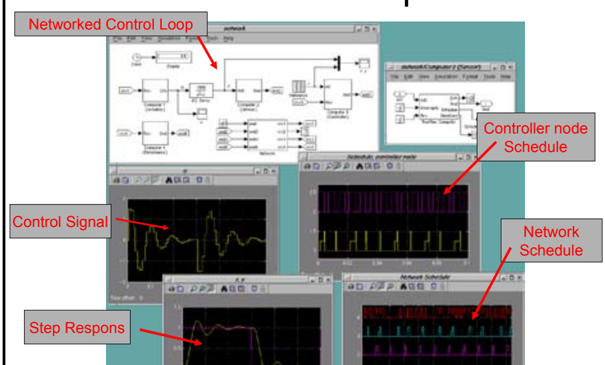
- A variety of pre-defined data-link layer protocols
  - CSMA/CD (Shared Ethernet)
  - CSMA/CA (CAN)
  - Round Robin
  - FDMA
  - TDMA
- The schedule shows the network traffic



TrueTime

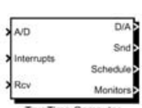
- Simulation of control loops under shared computing resources
- Co-simulation of controller task execution, network traffic, and continuous plant dynamics, in Simulink
- Applications:
  - Investigate the true, timely behaviour of control loops
  - Experimental platform for feedback scheduling, dynamic compensation schemes, ….
  - Simulate event-based control loops

Screen Dump



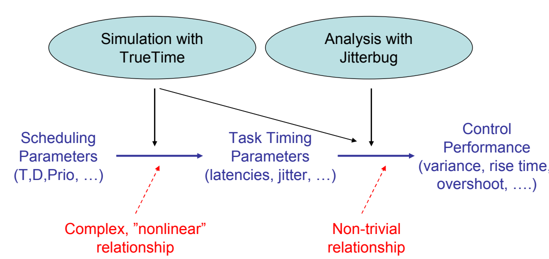
Computer Block

- Simulates an event-based real-time kernel
- Executes user-defined tasks and interrupt handlers
- Arbitrary user-defined scheduling policy
- External interrupts and timers
- Support for common real-time primitives (sleepUntil, wait/notify, setPriority, ..)
- Other features: context switches, overrun handlers, hooks, …



- Fixed priority
- EDF
- Cyclic executive

Tool Usage



Can we simplify this? **Presentation 2**

Conclusions

- Control and scheduling co-design is a promising area
- Requires tight collaboration between the control and computing communities
- Real-Time Computing Community:
  - A plethora of task models available
  - Focus on task models that are appropriate for control
- Control Community:
  - Focus on resource-constrained control

sub-task
hard
hardly weak??
incomplete
soft
multi-frame
weakly hard

ARTIST2

- Network of Excellence proposal to EU IST/Embedded System
- Will contain a cluster on control issues in embedded systems

FLEXCON

- Flexible Embedded Control Systems
- SSF/IT programme involving Lund, KTH, MdH, Skövde with industrial support from ABB and Enea
- Focus:
  - Provide flexibility and dependability in embedded control systems implemented with COTS component-based computing and communications technology
  - Use control-theoretical approaches as a way of handling uncertainty and provide flexibility
  - Quality-of-Service approaches in control systems
  - Testing-based verification of control systems
- URL: http://www.control.lth.se/FLEXCON

RTAS 2004 @ Toronto

- IEEE Real-Time and Embedded Technology and Applications Symposium
- Special track on real-time control

SAVE

- SSF/IT programme involving MdH, KTH, Linköping, Uppsala with industrial support from Volvo, ABB, Saab, Scania, Bombardier, …
- Goal:
  - establish an engineering discipline for systematic development of component-based software for safety critical embedded systems
- Focus on safety-critical vehicular systems
- URL: http://www.mrtc.mdh.se/SAVE