Timing problems and opportunities for embedded control systems - modeling and co-design

Prof. Martin Törngren, KTH, 
Embedded control systems/
 mechatronics/Machine Design
Royal Institute of Technology - KTH
Review and collaboration

- Work since the 90s
  - Example results
    - Scheduling theory better tailored to control systems
    - Relaxed timing requirements for control systems
    - Tools

- Cooperative work
  - Academia: Lund, Chalmers, MDH & Artist network
  - Industry: Arcticus, dSPACE, Scania, Volvo AB
  - People: Karl-Erik Årzen, Björn Wittenmark, Johan Nilsson, Magnus Gäfvert, Christer Norström, Kristian Sandström, Jan Torin, Henrik Lönn, Mats Andersson, Jad Elkhoury, Martin Sanfridson, Ola Redel, DeJiu Chen and Jan Wikander
Questions addressed in the talk:
- sampled control theory – feedback control

- Which kind of timing problems can be analyzed and handled?
- How can timing requirements be formulated and derived?
- What are the approaches for codesign of controllers and their embedded systems implementation?
- How can timing properties be expressed for analysis and/or synthesis?
Outline

- Background and motivation
  - Industrial control systems perspectives
  - Gaps and misconceptions

- Sampled control theory
  - Assumptions, properties and timing problems

- Codesign
  - Approaches
  - Abstractions

- Conclusions
Background

- Embedded control systems are evolving
  - More applications, more functions and modes
  - More networking and resource sharing
  - More timing issues in distributed systems
  - More safety concerns
  - Systems integration problems: feature interaction

- Despite work since the 70s, is still a gap from control theory to embedded systems
  - Pieces exist
  - Multidisciplinary challenge
Motion control demo

- Is this a hard or soft real-time system?
- Why type of control is exercised?
  - Feedforward?
    - And mode changes?
  - Feedback?
  - Hierarchical control?
    - Inner and outer loops!
- What are the timing constraints?
Note: Controller code is usually a small part of the total amount of code
Example application: stability control

Vehicle speed

Vehicle slip angle

Vehicle yaw rate

Source: ESC education - www.esceducation.org
Example application: vehicle stability control

Disturbances

Driver

Yaw/slip controller

Brake controller

Wheel dynamics

Vehicle dynamics

Engine controller

Engine dynamics

Different design settings!

Networks and vehicle computers

Example application: vehicle stability control
Cooperative driving competition to stimulate work towards traffic efficiency

- Smart use of communication between vehicles and infrastructure
- Cooperative Driving promises to results in:
  - Efficient and smooth driving (50% less traffic congestion)
  - Safety (8% less traffic accidents)
  - Clean driving (5% less CO₂ emission and fuel consumption)

www.gcdc.net
## Industrial engineering practice

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Inspired from Hanselman, 1998
Incorporation of system level timing analysis and synthesis – an exception

- Vaguely specified timing constraints
- Exceptions (examples)
  - Pragmatic use of RMA – a la RM handbook
    - Example: ESA since long uses RMA in analysis
  - Cyclic executives and synchronous languages
  - Volvo example
    - Volcano – Volvo CAN (Ken Tindell)
    - Rubus component mode and RTOS
- Increasing demand and new work
  - TADL (Timmo, ATESTT2), SymptaVision
  - ADLs, Marte
Gaps

• Impact of design decisions

• Need for appropriate interactions & abstractions
  • Example: Scheduling execution models: \{C, D, T\}
  • Simple but does not capture true requirements
  • Overconstraining.
Misconceptions

- Constant delay is better than a shorter but varying delay
  
  Average delay is most important
  Response time delay can not be avoided

- There is one suitable sampling period given by control design
  
  A range of feasible sampling periods
  Many aspects influence choice

- Control systems involve hard real-time constraints
  
  A deadline for one cycle is a HRT constraint
  
  Hard vs. Soft – two interpretations!
  Have to define what deadline refers to!
  Most control systems are soft in that missing one cycle can be tolerated
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- Feedback control systems
  - Assumptions, properties and timing problems

- Codesign
  - Methods
  - Abstractions

- Conclusions
Control systems and sampled control theory – recap

- Feedback provides robustness to disturbances
  - Sensitivity to sensor noise
  - Trade-off between performance and robustness
  - Delays are bad

- Control design in continuous or discrete-time

- Basic assumptions in sampled theory
  - Periodic sampling - external world synchronized with sampling instants
  - Zero order hold
  - Zero delay
Sampled data control systems perspective

Digital control system

- Constant sampling frequency
- Sampling: $y(t_k)$
- Controller: $u(t_k)$
- Actuation
- Antialiasing filter
- Synchronized actions

Sampling interval $h = t_k - t_{k-1}$
Sampling frequency $f = 1/h$
Typical timing constraints

- Bounded or constant sampling-actuation delay
  - Delay jitter
- Sampling period
  - Period jitter
- Sampling and/or actuation synchronization
- Response time from external event to loop

Characterization

- Timescale (fast vs. slow); Sensitivity (tight vs. non tight), Critical vs. non critical, …
Sampled control theory – dealing with constant delays

Solve the system equation

\[
\frac{dx(t)}{dt} = Ax(t) + Bu(t - \tau), \quad \tau < h
\]

\[
x(kh + h) - \Phi x(kh)
\]

\[
= \int_{kh}^{kh+h} e^{A(kh+h-s)} Bu(s - \tau) ds
\]

\[
= \int_{kh}^{kh+\tau} e^{A(kh+h-s)} B ds \ u(kh-h) + \int_{kh+\tau}^{kh+h} e^{A(kh+h-s)} B ds \ u(kh)
\]

\[
= \Gamma_1 u(kh - h) + \Gamma_0 u(kh)
\]

\[
\begin{pmatrix}
  x(kh + h) \\
  u(kh)
\end{pmatrix}
= \begin{pmatrix}
  \Phi & \Gamma_1 \\
  0 & 0
\end{pmatrix}
\begin{pmatrix}
  x(kh) \\
  u(kh-h)
\end{pmatrix}
+ \begin{pmatrix}
  \Gamma_0 \\
  I
\end{pmatrix} u(kh)
Constant delay compensation

- Delays
  - Limit control performance
  - Deteriorate phase margin; can lead to instability
  - Disturbance interpretation!

- Delay compensation is possible
  - Requires plant model and known delay
  - Removes dynamic effect!
  - Still degrades performance!
Controllers are bound by contracts to the ”plant”

In the sense that

- Controller parameters will refer to closed loop system dynamics – determined by the plant dynamics

- Timing constraints refer to open and closed loop system, and usage scenarios
  - Controller parameters will be a function of the chosen sampling period
  - Will be a function of expected delay if compensation is included in controller
    - Shorter actual delay can be as bad as long delay
Timing problems

- **Period**
  - Dynamics of closed loop!
  - Response time!
  - Rules of thumb

- **Transient errors / outage**
  - Somewhat similar to delays/jitter

- **Delays**
  - Average is most important

- **Jitter**
  - Variations in delay and/or period

- **Modes/operational dependence**
Time variations in embedded control systems

Output - minimize!

Update - sufficient during period

Note: Figure illustrates
- Time varying sampling period!
- Time varying delay!
Time variations – analysis

- Time varying delay and periods
  \[ x(t_{k+1}) = \Phi(h_k)x(t_k) + \Sigma \Gamma(h_k)u(t_{k-(nd-g)}) \]
  - Assuming models of plants and variations

- Jitter often modelled as stochastic
  - As opposed to “known” jitter
  - Markov chains for describing switching – e.g. overruns

- Transient behavior
  - Simulation
  - Robustness norms – Max gains

- Stationary
  - Cost functions
    \[ J = \int_0^\infty (x(t)^T Q_c x(t) + u(t)^T R u(t)) dt \]

- Jitterbug toolbox in Matlab (Lund)
Rules of thumb and heuristics (examples)

- Jitter of 10% in period and delay
  - Ok for performance assuming otherwise correct design
- Extreme jitter appears to be worst
  - The maximum values occur when the jitter changes between the two extreme values only.
  - Relevant for both delay and sampling jitter
- Transient errors:
  - Need to deal with overruns and errors anyway
  - Design for worst case + exceptions OR something more flexible?
Complications (and interesting problems!)

- Many settings and aspects!
  - Controller design and plant characteristics
  - Compensation or not for constant delay?
  - Type of variation, in period or delay
  - Combined variations
  - Where delays enter – makes a difference!

- MIMO systems and synchronization
- Multirate systems
- Iterative (anytime) algorithms
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Timing problems and opportunities for embedded control systems – 2011-09-16

What we want to achieve – codesign

Requirements

- Timing
- Computation
- Communication
- Accuracy
- Memory
- Power

Constraints

Platform

SW
HW

Requirements:
- Cost-efficiency
- Dependability
- Performance
- Flexibility
Example co-design problem formulation: Control and Scheduling

“Given a set of systems to be controlled and a computer system, design a set of controllers and schedule them as real-time tasks such that the overall control performance is optimized”

- Objective function can be based on control performance, but it could also be a measure such as the end-to-end delay
- Many opportunities for optimization
- However, challenging dependencies,
  - E.g. accounting for delay and period in scheduling
Controllers and real-time constraints

- Desired dynamics (speed) will determine the sampling period

\[ \sum \frac{C_i}{T_i} \leq 1; \quad C_i < T_i \ll t_{\text{rise}} \quad (f_{bw} \ll f_i < 1/C_i) \]

- Closed loop system characteristics determines delay bound, \( \tau_{\text{max}} \)

  - Discrete time: Check root locus, closed loop
  - Cont time: \( \tau_{\text{max}} \ll \phi_m / \omega_c \)
  - \( L_{io}(k) \leq \tau_{\text{max}} < R(k) \)

  - \( L_{io} \): Input output latency
  - \( R \): “Output” task response time
  - \( \phi_m, \omega_c \): phase margin, cross-over freq.
Deriving timing constraints in control design

- Specify a range of sampling periods
- Investigate tolerances to period jitter
  - Tolerances for jitter
- Investigate sensitivity to delays
  - Tolerances for constant delay
  - Max delay bound
  - Outage:
    - Max delay w.r.t. performance across cycles
    - Max delay w.r.t. stability
    - Safety may also be an issue
Example of relaxed timing constraints

- **Sampling instants:**
  - \( t_{\text{sample}}(k+1) = t_{\text{sample}}(k) + T \pm tol_T \)  
    Note: drift allowed

- **Actuation instants**
  - \( t_{\text{actuate}}(k) = t_{\text{sample}}(k) + \tau \pm tol_{Tao} \)  
    Note: Assuming constant delay

Alternative formulation for sampling instants:

- \( t_{\text{sample}}(k+1) = kT + T \pm tol_T \)  
  Note: without drift


“Synchronous” model
- Fixed period, zero delay & jitter

Constant delay

Inherent robustness constraints
- Set of periods, jitter tolerances
- Outage time constants

Extended robustness design
- Expected timing behavior as input to control design
- Redesign of controller for robustness
- Even on-line compensation possible

Dynamic configuration (QoS)
Approaches for design – “separation of concerns”

- “HRT approach”
  - Synchronous approach or cyclic executive
  - Make sure sampling period is met and delay as small as possible
  - Predictable
  - Works well for single loops but more complicated for multi-rate systems and multiple functionalities
  - Pessimistic resource utilization (WCET bounds)
  - Potentially costly
Approaches for co-design

- Exploit robustness of controllers to get more flexibility in embedded systems design
- Design controller explicitly to be robust to delays
- Run-time compensation/estimation
  - Measurement based active compensation
  - Gain-scheduling and feed-forward from disturbances
  - Applicable to delays and lost data
  - Run-time knowledge of delays is important
- Exploit run-time adaption for on-line optimization of resource usage
Timing abstractions for control and codesign

- Concern / viewpoint?
  - What is the model supposed to support?
    Analysis and/or Synthesis?
    For example
    - Control analysis,
    - Code generation,
    - Execution/infrastructure generation,
    Design parameters/Constraints (e.g. performance, power, etc.)

- Related questions
  - Which level of abstraction ?
  - Which formalism(s)?
  - Which tools?
KTH experiments

- Codesign environments: Control and embedded system in a combined model
  - XILO, Truetime (algorithms, resources, scheduling)
- Control design supported by "control abstractions" of embedded systems
  - AIDA (algorithms, delays, jitter, ...)
- Multiview modeling
  - Multiple concerns: functions, timing, architecture, embedded system behavior, reliability/safety, ...
- East-adl
- Tool integration (tight vs. loose integration)
Example co-design tool-set: AIDA

1. Control design in Simulink

2. Import the control design to the AIDA tool-set

3. The real-time implementation is modelled using the AIDA models. Functionality and architectural properties are analysed.

4. The resulting control design with embedded analysis results is exported to Simulink. The control performance can be analysed through simulation.

Architectural analysis
(e2e timing)

Import

Define mapping

Export

Design

Control analysis
EAST-ADL – An Automotive ADL extending Autosar

EAST-ADL modeling concepts
Timing Augmented Description Language (TADL)

<<functionalAnalysisArchitecture>>

fcn1:Function

inFlowPort

<<eventADLInFlowPort>>

stimulus

<<reactionConstraint>>

jitter = 2.0
nominal = 10.0
mode = startup

<<eventChain>>

fcn2:Function

outFlowPort

<<eventADLOutFlowPort>>

response

Sensing

Actuation

Courtesy of Volvo and the Timmo project
Timing abstractions for control and codesign - discussion

- Need to derive timing properties explicitly:
  - Period, delays, jitter, possible errors
- How to express the derived timing specifications from the control system?

Options

- Explicit blocks or annotations in the model, such as delays?
  - Used e.g. in AIDA for analysis, but not specifications
- Separate descriptions (separation of concerns)
  - Timing constraints
  - Dataflow, precedence
  - Algorithms
Increasing industrial demand!
Decoupling desirable but difficult to achieve

- At a minimum, to avoid headaches, need a better cross understanding

Combined treatment important for
- Cost constrained embedded systems
- Mission and safety critical systems
Conclusions – Timing problems and opportunities

- Embedded control systems
  - Sampled data systems; Co-design
  - Case for codesign methods and tools!

- In-depth topics for further elaboration
  - Comparison and evaluation of different abstractions
    - Relate to EDA and computer science abstractions!
    - Characterization of timing problems
  - Co-design methods for embedded control

- Tentative follow up talks
  - East-ADL
  - GCDC/Scoop
Related PhD theses supervised or cosupervised by Martin Törngren

- Enforcing Temporal Constraints in Embedded Control Systems, Kristian Sandström, 2001 (cosupervised)

- Response Time Analysis for Implementation of Distributed Control Systems, Ola Redell, 2003 (main supervisor)

- Topics in Modeling, Control, and Implementation in Automotive Systems, Magnus Gäfvert, 2003, (manager of the project in which the thesis was performed)

- Quality of Control and Real-time Scheduling - Allowing for time-variations in computer control systems, Martin Sanfridson, 2004, (main supervisor)

- Architecting and Modeling Automotive Embedded Systems, Ola Larses, 2005, (main supervisor)

- A Model Management and Integration Platform for Mechatronics Product Development, Jad Elkhoury, 2006 (main supervisor)

- Modeling and simulation of physical systems in a mechatronic context, Carl-Johan Sjöstedt, 2009, (main supervisor)
References (1)

References (2)

References (3)

References(4) – EAST-ADL
