ARBITRATED NCS: CASE STUDIES (PART 2)

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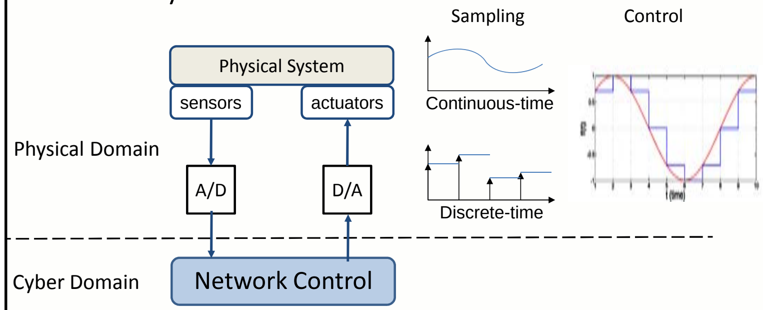
Sampled Data Systems

- Needs discrete-time tools
  - Implementation (digital controller)
  - Arbitration in the network allows transparency in delays



A Standard Sampled-Data Problem

- Physical system: $\dot{x}(t) = A_c x(t) + B_c u(t)$
- Multiple both sides by $e^{-A_c t}$

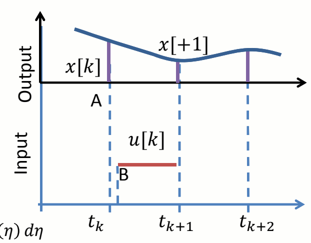
$$\frac{d}{dt}\left(e^{-A_c t}x(t)\right) = e^{-A_c t}B_c u(t)$$

- Integrate over $[t_k, t_{k+1}]$

$$e^{-A_c(kh+h)}x[k+1] - e^{-A_c kh}x(kh) = \int_{kh}^{kh+h} e^{-A_c\eta}B_c u(\eta)\, d\eta$$

  - Multiply both sides by $e^{A_c(kh+h)}$
  - $u(\eta) = u[k]$, over $[t_k, t_{k+1}]$
  - $x[k+1] = e^{A_c h}x[k] + \int_{kh}^{kh+h} e^{-A_c(\eta-kh-h)}B_c\, d\eta \cdot u[k]$

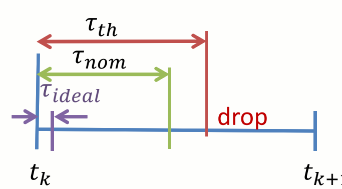
$$\Rightarrow \quad x[k+1] = Ax[k] + Bu[k]$$



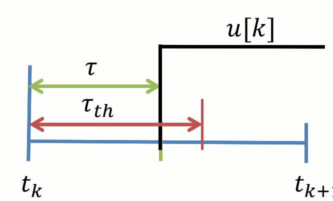
- Assumes that $u[k]$ is available immediately after t_k

Ideal, Nominal, Dropped cases

- Normal operations
  - Ideal $\tau = \tau_{ideal} \approx 0$
  - Nominal $\tau = \tau_{nom} < \tau_{th}$
- If $\tau > \tau_{th}$
  - Message is "dropped"



- Control input: $u[k]$



Plant-model for ANCS design: $\tau < h$

- Physical system: $\dot{x}(t) = A_c x(t) + B_c u(t)$
- With sampling, and integration over $[t_k, t_{k+1}]$

$$x[k+1] = e^{A_c h} x[k] + \int_{kh}^{kh+h} e^{-A_c(\eta - kh - h)} B_c\, u(\eta) d\eta$$

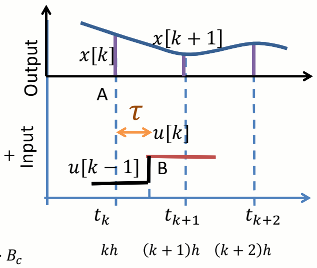
- $u(\eta) = u[k-1], \quad [t_k, t_k + \tau]$
- $u(\eta) = u[k], \quad [t_k + \tau, t_{k+1}]$

$$x[k+1] = e^{A_c h} x[k] + \int_{kh}^{kh+\tau} e^{-A_c(\eta - kh - h)} B_c\, d\eta \cdot u[k-1] + \int_{kh+\tau}^{kh+h} e^{-A_c(\eta - kh - h)} B_c\, d\eta \cdot u[k]$$

$$= \underbrace{e^{A_c h}}_{A} x[k] + \underbrace{\int_{h-\tau}^{h} e^{A_c \nu} d\eta \cdot B_c}_{B_2} \cdot u[k-1] + \underbrace{\int_{0}^{h-\tau} e^{A_c \nu} d\eta \cdot B_c}_{B_1} \cdot u[k]$$

$$\Rightarrow \boxed{x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1]}$$

- Assumes that τ is less than the sampling period h.



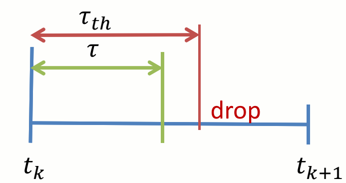
What happens if τ varies between 0 and h?

ANCS for varying τ – Case (i)

- Either $\tau < \tau_{th}$ (nominal)
- Or $\tau > \tau_{th}$ (drop)
- ANCS-Case 1 (ZOH):

u[k] = Simple feedback $\quad \tau < \tau_{th}$ (nominal)

u[k] = u[k − 1] $\quad \tau > \tau_{th}$ (drop)

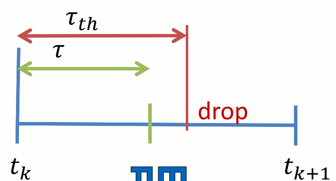


ANCS for varying τ – Case (ii)

- Either $\tau < \tau_{th}$ (nominal)
- Or $\tau > \tau_{th}$ (drop)
- ANCS-Case 2 (DCC):

u[k] = Augmented feedback $\quad \tau < \tau_{th}$ (nominal)

u[k]: Depends on the number of drops $\quad \tau > \tau_{th}$ (drop)



NOMINAL CONTROL DESIGN

$$0 < \tau < \tau_{th}\ (< h)$$

Control Design, $\tau < \tau_{th}$

- Plant dynamics, Discrete-time

$$x[k+1] = Ax[k] + B_2u[k-1] + B_1u[k]$$

- Control strategies:
  - Simple feedback

$$u[k] = Kx[k]$$

    K can be determined by LMI
  - Augmented feedback

$$u[k] = Kx[k] + Gu[k-1]$$

  K and G can be determined by LMI or LQR

Simple Feedback

- Plant

$$x[k+1] = Ax[k] + B_1u[k] + B_2u[k-1]$$

- Simple feedback

$$u[k] = Kx[k]$$

  Closed-loop:

$$x[k+1] = (A+BK)x[k] + B_2Kx[k-1]$$

- Find K using LMI (Linear Matrix Inequalities)

Finding K Using LMI (1)

- Closed loop with extended state

$$X[k+1] := \begin{bmatrix} x[k+1] \\ x[k] \end{bmatrix} = \begin{bmatrix} (A+BK) & B_2K \\ I & 0 \end{bmatrix} \begin{bmatrix} x[k] \\ x[k-1] \end{bmatrix}$$
$$= \tilde{A}X[k]$$

- Now we look for a Lyapunov function $V(x)$
  1. $V(X) = X[k]^T P X[k] > 0, V(0) = 0$
  2. $V(X[k+1]) - V(X[k]) < 0$
- These inequalities imply:
  1. $P \succ 0$
  2. $V(X[k+1]) - V(X[k]) = X^T[k](\tilde{A}^T P \tilde{A} - P)X[k] < 0$
     $\rightarrow \tilde{A}^T P \tilde{A} - P \prec 0$

  Multiply from left and right by $Q := P^{-1}$

$$Q\tilde{A}^T Q^{-1} \tilde{A} Q - Q \prec 0$$

Finding K Using LMI (2)

- Use the identity (Schur complement):
  $Q\tilde{A}^T Q^{-1} \tilde{A} Q - Q \prec 0 \Leftrightarrow \begin{bmatrix} -Q & Q\tilde{A}^T \\ \tilde{A}Q & -Q \end{bmatrix} \prec 0$
- Noting
  $\tilde{A} := \begin{bmatrix} (A+BK) & B_2K \\ I & 0 \end{bmatrix}$ $(X[k+1] = \tilde{A}X[k])$
  - Choose $Q = \begin{bmatrix} Q_1 & 0 \\ 0 & Q_1 \end{bmatrix}$
- Use the following LMI to find Q_1 and E:
  1. $Q_1 > 0$
  2. $\begin{bmatrix} -Q_1 & * & * & * \\ 0 & -Q_1 & * & * \\ AQ_1 + B_1E & B_2E & -Q_1 & * \\ Q_1 & 0 & 0 & -Q_1 \end{bmatrix} \prec 0$

$$\rightarrow K = EQ_1^{-1}$$

Augmented Feedback

- Plant
  $$x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1]$$
- Improve "Simple Feedback" using controller
  $$u[k] = Kx[k] + Gu[k-1]$$
  - Allows more control strategies (LMI, LQR...)
- Define Augmented State
  $$X[k] = [x^T[k], u^T[k-1]]^T$$
- Closed-loop system
  $$X[k+1] = \begin{bmatrix} A_1 + B_{11}K & B_{12} + B_{11}G \\ K & G \end{bmatrix} X[k]$$

Finding K and G using LMI

Choose Positive Definite Q_1 and Q_2 such that the following Linear Matrix Inequalities (LMI) are satisfied for some matrices E and F:

$$\begin{bmatrix} -Q_1 & \mathbf{0} & * & * \\ \mathbf{0} & -Q_2 & * & * \\ A_1Q_1 + B_{11}E & B_{12}Q_2 + B_{11}F & -Q_1 & \mathbf{0} \\ E & F & \mathbf{0} & -Q_2 \end{bmatrix} \prec \mathbf{0},$$

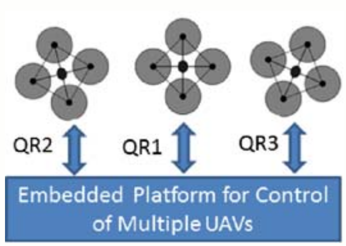
with

$$K = EQ_1^{-1} \qquad G = FQ_2^{-1}.$$

Example: Multiple UAVs

- Control three UAVs simultaneously through a network

$$\begin{cases} \ddot{x} = g\theta \\ \ddot{y} = -g\phi \\ \ddot{z} = \frac{\Delta U_1}{m} \\ \ddot{\phi} = \frac{L}{I_x} U_2 \\ \ddot{\theta} = \frac{L}{I_y} U_3 \\ \ddot{\psi} = \frac{1}{I_z} U_4 \end{cases}$$

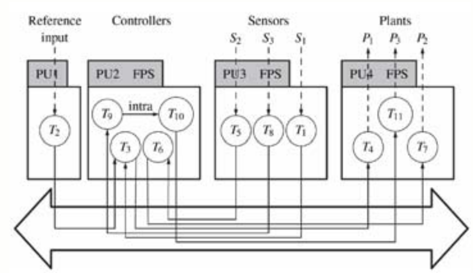


- Sharing resources cause delays in the system

Annaswamy et. al, "Arbitrated Network Control Systems: A co-design of control and platform for cyber-physical systems," Control of Cyber-Physical Systems, Lecture Notes in Control and Information Sciences, Vol. 449, Ed: D.C. Tarraf, Springer Verlag, 2013.

Design in Presence of Delays

- QR1: sampling time 15ms
- TDMA scheduler, cycles of lengths c=10ms.
- Use service and arrival curves and real-time calculus
- Maximum delay of control messages in QR1: 14.6ms



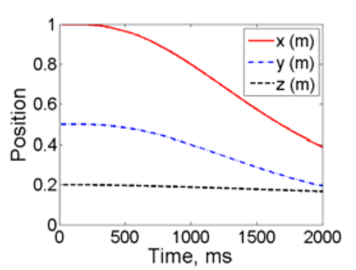
Performance using Augmented Feedback

An arbitrary $\tau_{nom} < \tau_{worst}$ was chosen for control design

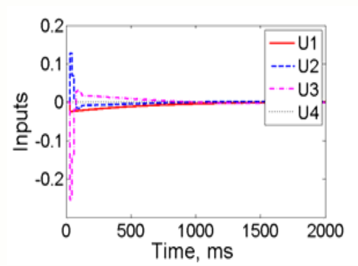
$\tau_{worst} = 14.6ms$

τ_{nom}= 10ms

Position of QR1



Inputs to QR1

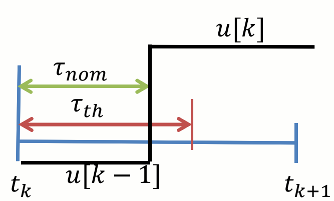


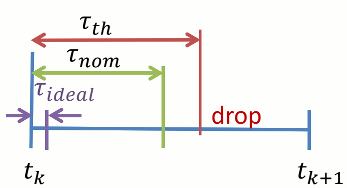
In all cases, $\tau < \tau_{th}$ $- nominal\ case!$

WHAT HAPPENS IF $\tau > \tau_{th}$?

Ideal, Nominal, Dropped cases

- Normal operations
  - Ideal $\tau = \tau_{ideal} \approx 0$
  - Nominal $\tau = \tau_{nom} < \tau_{th}$
- If $\tau > \tau_{th}$
  - Message is "dropped"
- Control input: $u[k]$

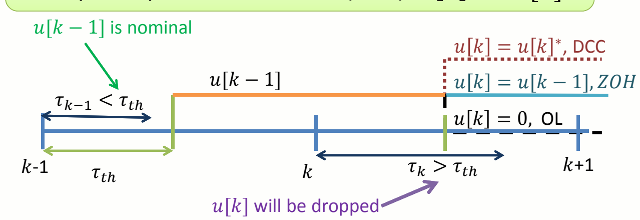




Dropped case

- Dropped Signals ($\tau > \tau_{th}$)
  - $u[k]$ is arriving late and may not be useful
- Control design must accommodate the "drop": Three possibilities
  - Revert to open-loop: $u[k] = 0$
  - Zero-order hold: $u[k] = u[k-1]$
  - Drop Compensation Control (DCC): $u[k] = u^*[k]$

Rest of the talk

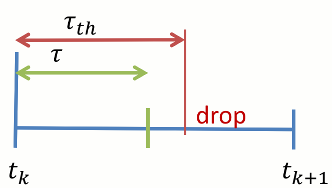


ANCS for varying τ

- Either $\tau < \tau_{th}$ (nominal)
- Or $\tau > \tau_{th}$ (drop)
- ANCS-Case 1 (ZOH):

$\mathrm{u[k]} = \text{Simple feedback} \quad \tau < \tau_{th}$ (nominal)

$\mathrm{u[k]} = \mathrm{u[k-1]} \quad \tau > \tau_{th}$ (drop)

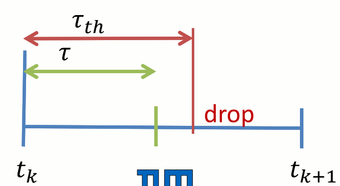


ANCS for varying τ – Case (ii)

- Either $\tau < \tau_{th}$ (nominal)
- Or $\tau > \tau_{th}$ (drop)
- ANCS-Case 2 (DCC):

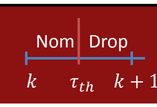
$\mathrm{u[k]} = \text{Augmented feedback} \quad \tau < \tau_{th}$ (nominal)

$\mathrm{u[k]}$: Depends on the number of drops $\quad \tau > \tau_{th}$ (drop)



ANCS – CASE (I)

Case (i): ZOH, Simple Feedback



Nominal + Drop: $\begin{cases} \text{Compute nominal } u[k] & \text{if } \tau \le \tau_{th} \\ \text{Drop } u[k] & \text{if } \tau > \tau_{th} \end{cases}$

Leads to a switching system:

- Nominal

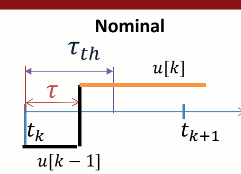
$$\begin{cases} u[k] = K\,x[k] & \text{if } \tau \le \tau_{th} \\ x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1] \end{cases}$$

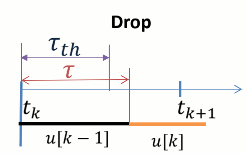
- 1 Drop

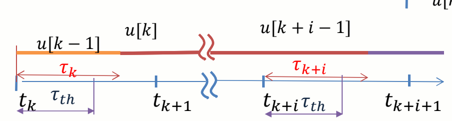
$$\begin{cases} u[k] = u[k-1] & \text{if } \tau > \tau_{th} \\ x[k+1] = Ax[k] + (B_1 + B_2)u[k-1] \end{cases}$$

- i Drops

$$\begin{cases} u[k] = u[k-i] & \text{if } \tau > \tau_{th} \\ x[k+1] = Ax[k] + (B_1 + B_2)u[k-i] \end{cases}$$





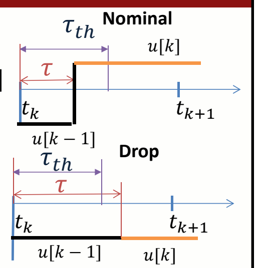


D. Soudbakhsh, L.X. Phan, O. Sokolsky, I. Lee, and A.M. Annaswamy. Co-design of control and platform with dropped signals. ICCPS 2013.

Dropped Mode Modeling

- Nominal ($\tau \le \tau_{th}$)
  - $x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1]$
- Dropped ($\tau > \tau_{th}$)
  - $u[k] = u[k-1]$
  - $x[k+1] = Ax[k] + (B_1 + B_2)u[k-1]$
  - $x[k]$ is not available, use $x[k-1]$
  - $x[k+1] =$

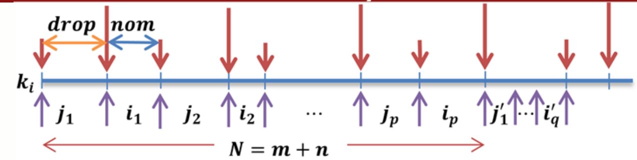
$$A\overbrace{(Ax[k-1] + B_1 u[k-1] + B_2 u[k-2])}^{x[k]} + (B_1 + B_2)u[k-1]$$



- For arbitrary i:
  - $X[k+1] = \begin{bmatrix} A^{j+1} + A^j B_1 K + \Sigma_{\ell=0}^{j-1} A^\ell BK & A^j B_2 K \\ I & 0 \end{bmatrix} X[k-1]$

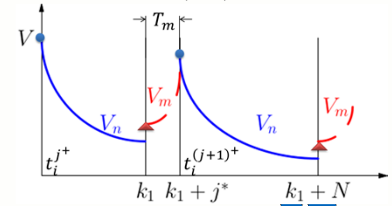
$$:= A_m^{(j)} X[k-j]$$

An MLF Approach for the Overall Switched System



Control messages with nominal (i's) and drops (j's)

$$\begin{cases} X[k+i_1] = A_m^{(j_1)} X[k] & \text{(Dropped Mode)} \\ X[k+N] = A_n^{i_p} A_m^{(j_p)} \cdots A_n^{i_2} A_m^{(j_2)} A_n^{i_1} X[k+i_1] & \text{(Stable Mode)} \end{cases}$$



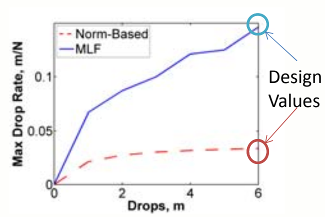
Multiple Lyapunov Functions

Switched-System Stability

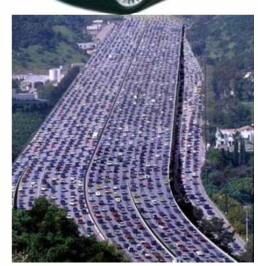
Theorem 1: $X[k+N] = A_n^{i_p} A_m^{(j_p)} \cdots A_n^{i_2} A_m^{(j_2)} A_n^{i_1} A_m^{(j_1)} X[k]$

Over every interval N, there exists m such that if there are at most m drops, then the system is stable.

- Drops can be non-consecutive
- LMI-based analysis
- Multiple Lyapunov Functions
  - Stable mode
  - Dropped mode
- Less conservative than a norm-based approach

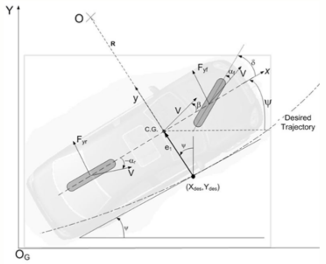


Example: DES & Transportation



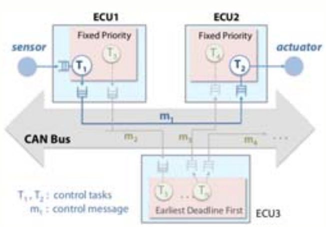
- In today's car:
  - over 80 ECUs
  - over 100 sensors
    - oxygen sensor
    - MAP sensor
    - engine temperature sensor
    - throttle position sensor
    - knock sensor
  - Information exchanged through a shared communication bus
- Multiple control applications
  - power train
  - vehicle dynamics
  - platoon dynamics

Case Study – Lane Keeping System



$$\frac{d}{dt}\begin{bmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{bmatrix} = A_c \begin{bmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{bmatrix} + B_c\delta + G\psi_{des}$$

e_1: position error e_2: yaw angle error



Goal: Help drivers to avoid unintended lane departure

- Higher priority tasks in ECU1 and ECU2 – can preempt control task
- ECU3 can place additional load on the CAN bus

Case (i): results (Strategy 1)

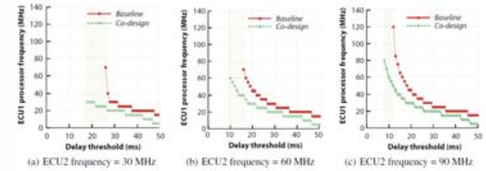
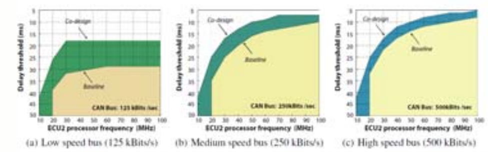


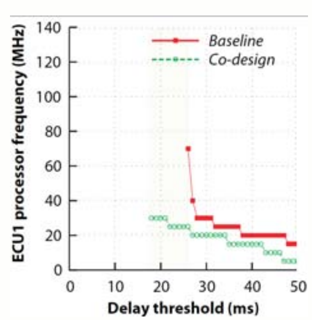
Figure 15: ECU1 processor frequency for different delay thresholds.



- Our approach enables efficient design space exploration
- Co-design always outperforms the baseline approach
- Resource savings increase on more constrained platforms
- Co-design provides a larger feasible design space

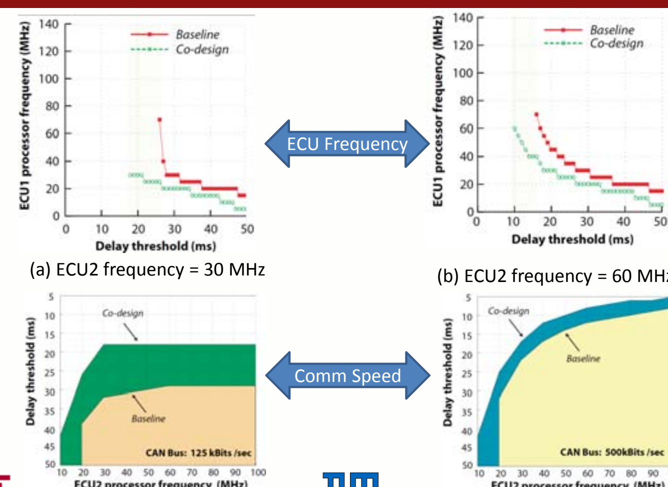
Resource Savings

- Resource Saving
- Impact of delay threshold (τ_{th})



- Co-design always outperforms the baseline approach
- Resource savings increase on more constrained platforms

Case (i): Design Space Exploration



Improve Case (i) Using DCC

- Case (i)
  - Considered varying delay: Nominal or Drop
  - For "nominal" use simple feedback
  - For "drop": Reuse old input – ZOH
  - Stability analysis took into account switch between nominal and drop (and in the latter, number of drops)
  - MLF used for proof of stability
  - Less conservative and better use of resources
- Case (ii)
  - For "nominal" use augmented feedback
  - For "drop", use an estimate of state instead of actual measurement

ANCS – CASE (II)

Case (ii): Drop compensation Control (DCC)

- Previous strategy
  - Nominal delay-aware
  - Zero order hold (ZOH) for drops $u[k] = u[k-1]$
- Here, use Drop Compensation Control (DCC)

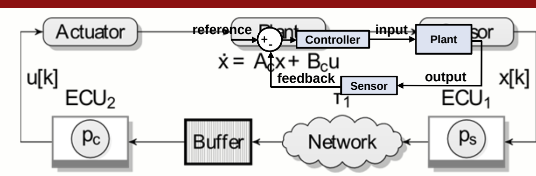
Example for one drop:

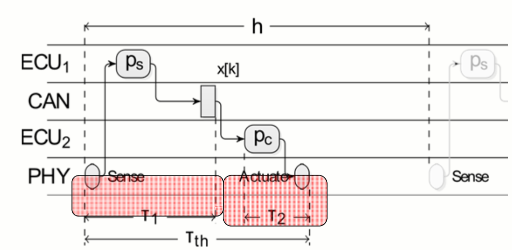
$$u[k] = \begin{cases} K_0 x[k] + G_0 u[k-2], & \tau_k \le \tau_{th} \\ K_1 \hat{x}[k] + G_1 \hat{u}[k-1], & \tau_k > \tau_{th} \end{cases}$$

$$\begin{cases} \hat{x}[k] = Ax[k-1] + (B_1 + B_2)u[k-2] \\ \hat{u}[k-1] = K_0 x[k-1] + G_0 u[k-2] \end{cases}$$

* M. Kauer, , D. Soudbakhsh, D. Goswami, S. Chakraborty, and A.M. Annaswamy. Fault-tolerant control synthesis and verification of distributed embedded systems. DATE 2014.

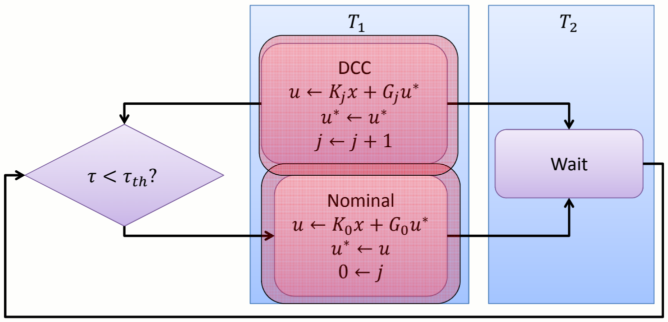
Problem Statement





$$x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1]$$

Case (ii) Summary of Control Design



Utilize LMI formulation to design K_j, G_j

Case (ii) Stability Design

Given: System $x[k+1] = Ax[k] + B_1 u[k] + B_2 u[k-1]$ experiences at most m consecutive drops.
Variables: Matrices E_j, F_j, pos. def. matrices $Q_1, Q_2 \geq 0$
Choose: $K_j = E_j Q_1^{-1}, G_j = F_j Q_2^{-1}$

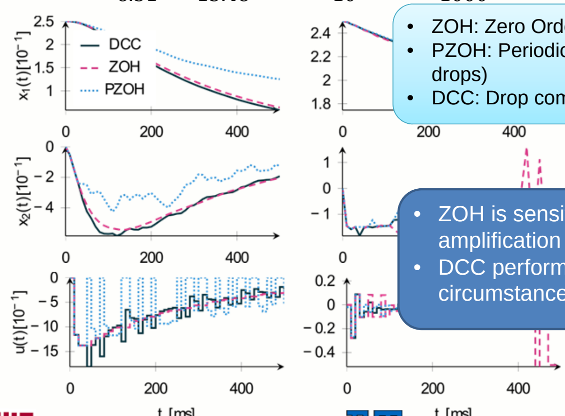
Need: $A_n^T P A_n - \gamma P < 0$ and $A_d^{(j)T} \mathrm{P} \mathrm{A}_\mathrm{d}^{(j)} - \gamma P < 0$
Then: Exponential stability follows from existence of CQLF

- Schur Complement
- Inverse Multiplication ($Q = P^{-1}$)
- Note $A_d^{(j)}$ give the predicted state values
  Interaction of $A_d^{(j)}$ with matrix variables gives L_j.

SOLVE: $\begin{bmatrix} -\gamma Q & * \\ L_j & -Q \end{bmatrix} < 0$

Case (ii) Results

$A_c = \begin{bmatrix} 0 & 1 \\ 6.31 & -15.48 \end{bmatrix}, B_c^1 = \begin{bmatrix} 0 \\ 10 \end{bmatrix}, B_c^2 = \begin{bmatrix} 0 \\ 1000 \end{bmatrix}$



- ZOH: Zero Order Hold
- PZOH: Periodic ZOH (Open-loop drops)
- DCC: Drop compensation Control

- ZOH is sensitive to high input amplification (B_c^2 right)
- DCC performs well under both circumstances.

Summary (Part 4)

- ANCS: Use information about the varying delays experienced by messages
  - Classify as nominal ($\tau \leq \tau_h$), or drop ($\tau \geq \tau_h$)
- Case (i)
  - Use simple feedback for nominal case
  - Use ZOH for dropped case
  - Use Multiple Lyapunov Function tool to estimate worst maximum allowable drops

Summary (Part 4) – contd.

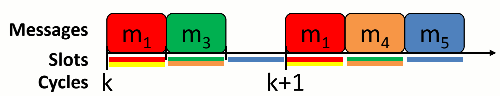
- ANCS: Use information about the varying delays experienced by messages
  - Classify as nominal $(\tau \leq \tau_h)$, or drop $(\tau \geq \tau_h)$
- Case (ii)
  - Use augmented feedback for nominal case
  - Use state-estimate from plant model for dropped case (can be done for any number of drops)
  - Use Common Lyapunov Function tool to estimate worst maximum allowable drops

Overall Summary

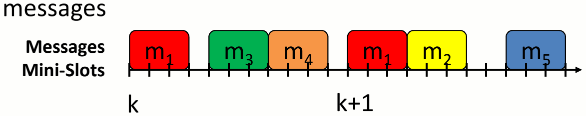
- Embedded Control Systems
  - Introduction
  - Closing the gap between theory and implementation
  - Co-design of network and control to optimize resource utilization and control performance
- Control theory fundamentals
  - Use of Feedback
  - Control performance metrics
    - Transient and steady-state
    - Trade-off between speed/accuracy and control effort
- ANCS
  - Transparency and flexibility in the network: Delays known/can be designed
  - Use of switching systems and their design for stability

Other work: Hybrid Protocols

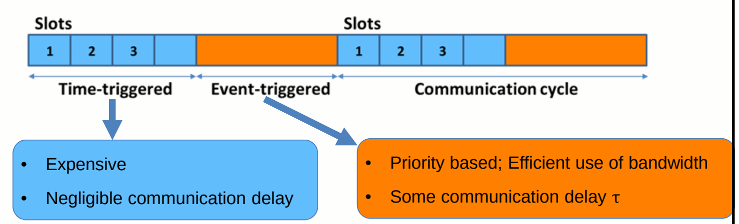
1. Time-Triggered (TT)
   - Messages are sent only at their predefined slots



2. Event-Triggered (ET)
   - Messages are assigned priorities to arbitrate for access
   - High priority messages are sent before low priority messages



Properties of Hybrid Protocols



$$x[k+1] = Ax[k] + B\_1u[k] \qquad \text{(TT)}$$

$$x[k+1] = Ax[k] + B_1u[k] + B_2u[k-1] \qquad \text{(ET)}$$

- Determine ideal hybrid sequence leading to minimal TT slots and optimal control performance
- Determine ideal hybrid sequence when plant parameters are not known.

Publications

- Delay – fixed
  - $\tau_{known} + \tau_{unknown}$ (1)
  - < h or (h, 2h) (2)
- Varying Delays
  - τ_h or > τ_h (3,4,5)
  - τ's are in MIMO systems and inter-dependent (6)

1. H. Voit and A.M. Annaswamy. Adaptive control of a networked control system with hierarchical scheduling. In American Control Conference (ACC), 2011, pages 4189–4194, June 2011
2. A.M. Annaswamy, D. Soudbakhsh, R. Schneider, D. Goswami, and S. Chakraborty. Arbitrated network control systems: A co-design of control and platform for cyber-physical systems. Ed. D.C. Tarraf, Control of Cyber-Physical Systems, volume 449 of Lecture Notes in Control and Information Sciences, pages 339–356. Springer International Publishing, 2013. ISBN 978-3-319-01158-5.
3. M. Kauer, D. Soudbakhsh, D. Goswami, S. Chakraborty, and A.M. Annaswamy. Fault-tolerant control synthesis and verification of distributed embedded systems. In Design, Automation & Test in Europe, Dresden, Germany, 2014.
4. P. Kumar, D. Goswami, S. Chakraborty, A.M. Annaswamy, K. Lampka, and L. Thiele. A hybrid approach to cyber-physical systems verification. In 2012 49th ACM/EDAC/IEEE DAC, pages 688–696, June 2012.
5. D. Soudbakhsh, L.X. Phan, O. Sokolsky, I. Lee, and A.M. Annaswamy. Co-design of control and platform with dropped signals. In The 4th ACM/IEEE International Conference on Cyber-Physical Systems [ICCPS'13], April 2013
6. D. Soudbakhsh, A. Chakrabortty, A.M. Annaswamy, "Computational Co-Designs for Wide-Area Control of Power Grids," submitted to The 53rd IEEE Conference on Decision and Control (CDC 2014), Los Angeles, CA..

Publications

- Multi-mode: TT-ET
  - Parameters unknown (1,2)
  - Monotonic (3,4) and non-monotonic system response (5)

1. H. Voit, A.M. Annaswamy, R. Schneider, D. Goswami, and S. Chakraborty. Adaptive switching controllers for systems with hybrid communication protocols. In American Control Conference (ACC), 2012, pages 4921–4926, June 2012.
2. H. Voit, A.M. Annaswamy, R. Schneider, D. Goswami, and S. Chakraborty. Adaptive switching controllers for tracking with hybrid communication protocols. In 2012 IEEE 51st Annual Conference on Decision and Control (CDC), pages 4121–4126, Dec 2012. doi: 10.1109/CDC.2012.6426568.
3. A. Masrur, D. Goswami, R. Schneider, H. Voit, A.M. Annaswamy, and S. Chakraborty. Schedulability analysis of distributed cyber-physical applications on mixed time-/event-triggered bus architectures with retransmissions. In SIES, pages 266 –273, june 2011.
4. A. Masrur, D. Goswami, S. Chakraborty, J.J. Chen, A.M. Annaswamy, and A. Banerjee. Timing analysis of cyber-physical applications for hybrid communication protocols. In Design, Automation Test in Europe Conference Exhibition (DATE), 2012, pages 1233–1238, March 2012. doi:10.1109/DATE.2012.6176681.
5. L. Maldonado, A. Annaswamy, D. Goswami, and S. Chakraborty, "Exploiting non-monotonicity of system dynamics for tighter resource dimensioning in CPS," Active-adaptive Control Laboratory, Massachusetts Institute of Technology, Technical Report, July 2012.

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Looking Ahead

Evolutionary Webs – Science for CPS

- Design a Cyber-physical System that evolves to meet the needs of the physical system and accommodates new devices – sensors, processors, memory, actuators…
- Design tools for analysis and synthesis of CPS – hybrid, hierarchical, distributed, arbitrated, networked system of cyber-physical systems

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