EINDHOVEN UNIVERSITY OF TECHNOLOGY

Event-triggered Control and Communication in Networked Systems

Maurice Heemels

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Cooperative driving application

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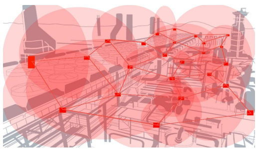
Cooperative Adaptive Cruise Control (CACC)

Movie CACC vs ACC

Introduction: We live in a hyperconnected world

Connected Vehicles

Smart Grid



Industrial internet

Cooperating Robotics

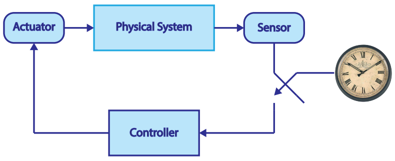
- Use of advanced communication technologies lead to novel applications and better control performance
- However, if communication networks are overloaded, these benefits are lost
  - long delays, many packet losses, etc.

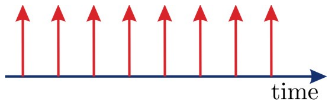
Key question: When to exchange data between sensors, controllers and/or actuators s.t.

1. desirable stability and performance properties are guaranteed
2. limitations of implementation resources such as bandwidth, power usage, etc. of communication networks are incorporated

Introduction

Control over packet-based communication networks

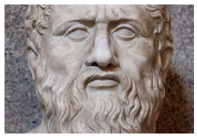




- Time-triggered control: Control tasks executed periodically & triggered by time: $t_{k+1} = t_k + h$

- Time-triggered paradigm "speaks because it has to say something," not because "it has something to say": Inefficient usage of resources

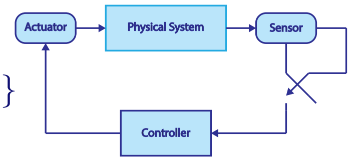
"Wise men speak because they have something to say, fools because they have to say something" – Plato $\sim$ 370 BC

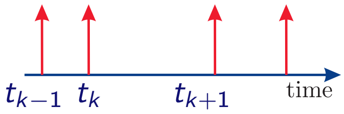


- Event-triggered control: Only speak when there is something to say: feedback in resource usage

Transmission times:

$$t_{k+1} = \min\{t > t_k \mid |y(t) - \hat{y}(t)| \geqslant \delta\}$$





Introduction

Movie inverted pendulum [time-triggered vs event-triggered communication]

- Same performance as 1 [kHz] time-triggered controller at $\sim$ 1% of transmissions

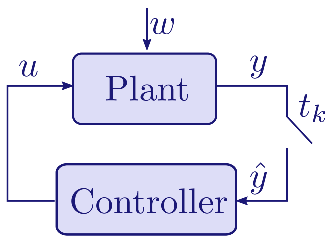
Outline

- Event-triggered control (ETC): Requirements
- Modelling systems with packet-based communication: hybrid systems
- Event generators:
  - Basic schemes (< 2012)
  - Challenges
  - Advanced schemes ($\geqslant 2012$)
  - Focus: Periodic event-triggered control
- Cooperative driving
- Conclusions

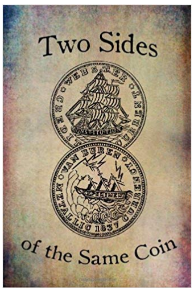
Event-triggered control

Requirements

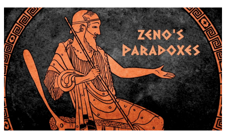
$$t_{k+1} = \min\{t > t_k \mid |y(t) - \hat{y}(t)| \geqslant \delta\}$$



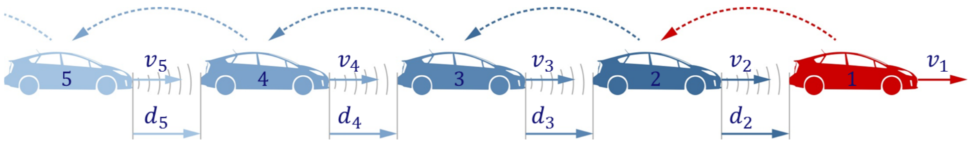
- Quality of Control: Stability, Performance, Robustness



- Resource Utilisation:
  - Warning: Zenoness: An infinite number of transmissions in finite time
    - Strong non-Zenoness: There is $T > 0$ s.t. transmission intervals $t_{k+1} - t_k \geqslant T$ for all $k \in \mathbb{N}$
  - Reduced communication w.r.t. time-triggered control
    - Consistency!

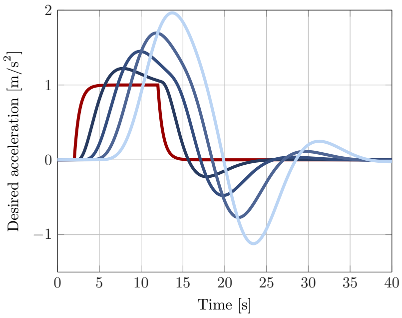


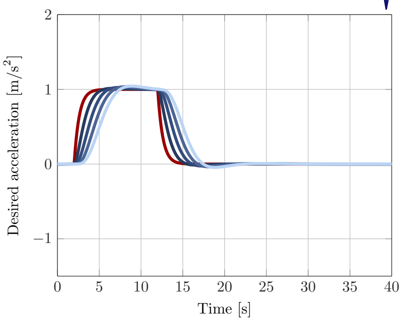
Requirements for CACC

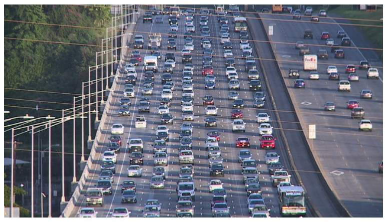


- Vehicle following: Maintain a small 'headway-time' (stability property)
- String stability: disturbance attenuation along the vehicle string ($\mathcal{L}_2$-gain $\leqslant 1$)

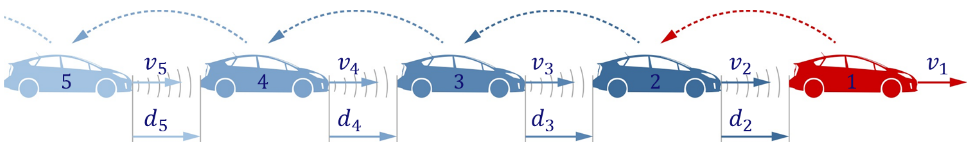
$$\|u_n\|_{\mathcal{L}_2} \leqslant \|u_{n-1}\|_{\mathcal{L}_2} \text{ with } \|u_n\|_{\mathcal{L}_2} = \sqrt{\int_0^\infty \|u_n(t)\|^2 dt}$$



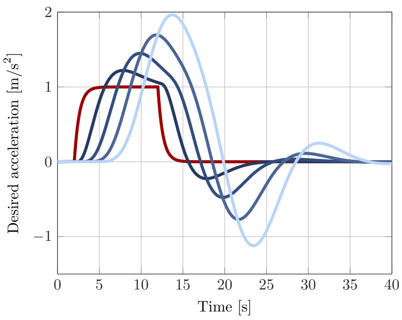


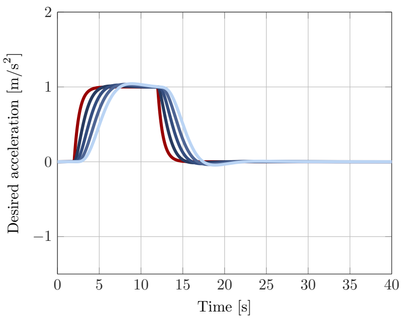


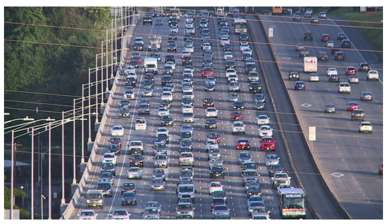
Requirements for CACC



- Vehicle following: Maintain a small 'headway-time' (stability property)
- String stability: disturbance attenuation along the vehicle string ($\mathcal{L}_2$-gain $\leqslant 1$)
- Reduced communication to avoid overload (strong non-Zenoness)
- Partial information case: Local triggers not having access to full state of platoon







Outline

- Event-triggered control (ETC): Requirements
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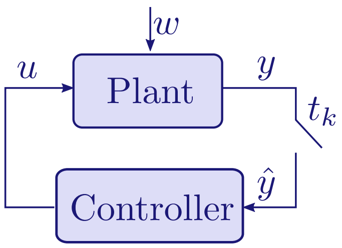
Modelling systems with packet-based communication

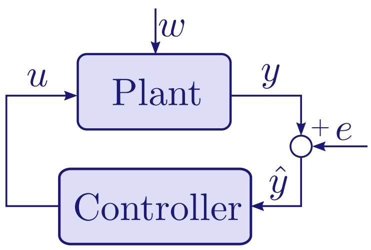
Hybrid systems

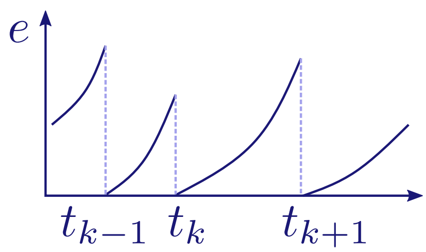
Plant : $\dot{x}_p = f_p(x_p, u, w)$, $y = g_p(x_p)$



Controller: $\dot{x}_c = f_c(x_c, \hat{y})$, $u = g_c(x_c)$

- $\hat{y}(t_k) = y(t_k)$ at transmission times t_k, $k \in \mathbb{N}$
- Predictor for $\hat{y}$ between transmissions: $\frac{\mathrm{d}}{\mathrm{d}t}\hat{y} = f_y(\hat{y}, u)$ (= 0 when ZOH)
- Sampling-induced error $e = \hat{y} - y$

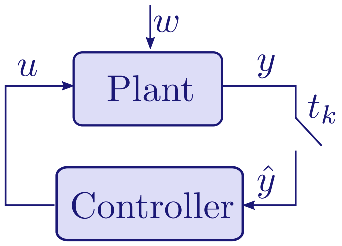




Modelling systems with packet-based communication

Hybrid systems

$$\text{Plant}: \quad \begin{aligned} \dot{x}_p &= f_p(x_p, u, w) \\ y &= g_p(x_p) \end{aligned}$$



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- $\hat{y}(t_k) = y(t_k)$ at transmission times t_k, $k \in \mathbb{N}$
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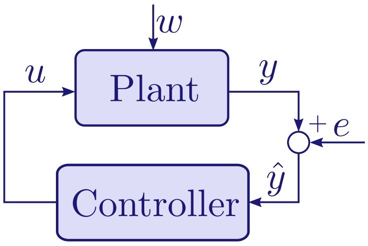


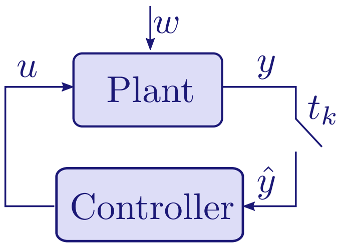
Physical part with $x = (x_p, x_c)$:

$$\dot{x} = f(x, e, w) = \begin{bmatrix} f_p(x_p, g_c(x_c), w) \\ f_c(x_c, g_p(x_p) + e) \end{bmatrix}$$

Modelling systems with packet-based communication

Hybrid systems

$$\text{Plant}: \quad \begin{aligned} \dot{x}_p &= f_p(x_p, u, w) \\ y &= g_p(x_p) \end{aligned}$$



$$\text{Controller}: \quad \begin{aligned} \dot{x}_c &= f_c(x_c, \hat{y}) \\ u &= g_c(x_c) \end{aligned}$$

- $\hat{y}(t_k) = y(t_k)$ at transmission times t_k, $k \in \mathbb{N}$
- Predictor for $\hat{y}$ between transmissions: $\frac{\mathrm{d}}{\mathrm{d}t}\hat{y} = f_y(\hat{y}, u)$ $\qquad$ ($= 0$ when ZOH)
- Sampling-induced error $e = \hat{y} - y$

Cyber part: (ZOH)

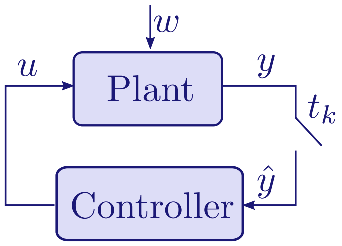
$$\dot{e} = g(x, e, w) := -\frac{\partial g_p}{\partial x_p} f_p(x_p, g_c(x_c), w), \qquad \text{when } t \neq t_k$$

$$e^+ = 0, \qquad \text{when } t = t_k$$

Modelling systems with packet-based communication

Hybrid systems

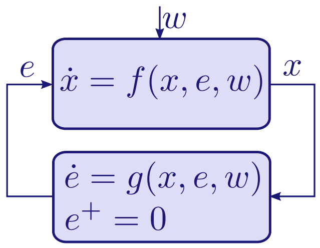
Plant : $\dot{x}_p = f_p(x_p, u, w)$
$y = g_p(x_p)$



Controller: $\dot{x}_c = f_c(x_c, \hat{y})$
$u = g_c(x_c)$

Hybrid system [1]

$$\begin{aligned} \dot{x} &= f(x, e, w), && \text{when } t \neq t_k \\ \dot{e} &= g(x, e, w), && \text{when } t \neq t_k \\ e^+ &= 0, && \text{when } t = t_k \end{aligned}$$



- How to determine $\{t_k\}_{k \in \mathbb{N}}$ in order to guarantee stability and performance?

[1] Goebel, Sanfelice, Teel, *Hybrid Dynamical Systems*, Princeton, 2012.

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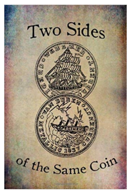
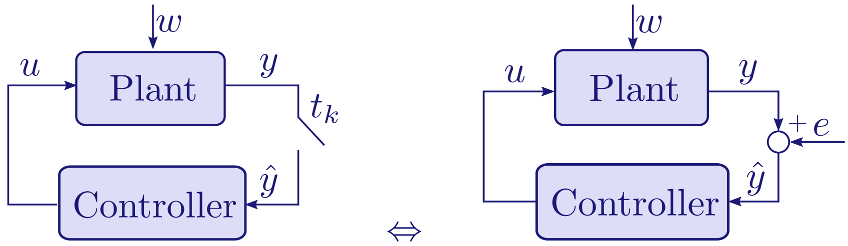
ETC for disturbance / partial information case





$e = y - \hat{y}$

Event generator		
Relative	$\lvert e\rvert \geqslant \sigma \lvert y\rvert$	[3]
Absolute	$\lvert e\rvert \geqslant \delta$	[1,4-7]
Mixed	$\lvert e\rvert \geqslant \sigma\lvert y\rvert + \delta$	[2]

[1] Heemels, Sandee, van den Bosch, *Analysis of event-driven controllers for linear systems*, IJC 2008
[2] Donkers, Heemels, *Output-Based Event-Triggered Control with Guaranteed L_∞-gain ...*, TAC 2012
[3] Tabuada, *Event-triggered real-time scheduling of stabilizing control tasks*, TAC 2007
[4] Yook, Tilbury, Soparkar, *Trading computation for bandwidth: Reducing communication in distributed control ...*, TCST 2002
[5] Miskowicz, *Send-on-delta concept: An event-based data-reporting strategy*, Sensors 2006
[6] Kofman, Braslavsky, *Level crossing sampling in feedback stabilization under data-rate constraints*, CDC 2006
[7] Lunze and Lehmann, *A state-feedback approach to event-based control*, Automatica 2010

ETC for full (state) information case (no disturbances)

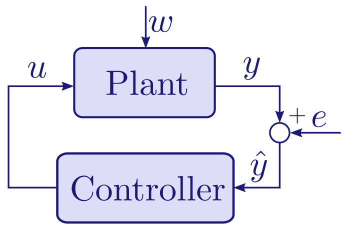
- No disturbance $w = 0$ and full information $y = x$

Event generator		non-Zenoness
Relative	$\lvert e\rvert \geqslant \sigma\lvert x\rvert$	global
Absolute	$\lvert e\rvert \geqslant \delta$	semi-global
Mixed	$\lvert e\rvert \geqslant \sigma\lvert x\rvert + \delta$	global

- Strong non-Zeno: there is $T > 0$ s.t. transmissions intervals $t_{k+1} - t_k \geqslant T$, $k \in \mathbb{N}$
- Global: lower bound on transmission intervals holds for all initial states
- Semi-global: lower bound on transmission interval depends on size of initial state (and goes to zero for large states)

ETC for full (state) information case (no disturbances)

- No disturbance $w = 0$ and full information $y = x$



Event generator	non-Zenoness	control properties
Relative $\lvert e\rvert \geqslant \sigma\lvert x\rvert$	global	asymptotic stability
Absolute $\lvert e\rvert \geqslant \delta$	semi-global	practical stability
Mixed $\lvert e\rvert \geqslant \sigma\lvert x\rvert + \delta$	global	practical stability

- Asymptotic stability $x(t) \to 0$ when $t \to \infty$
- Practical stability $x(t) \to \mathcal{B}(0, \varepsilon)$ when $t \to \infty$ with $\varepsilon > 0$
- Analysis can be found in [1,2,3]
- Relative triggering looks promising, but fragile...

[1] Borgers, H., *Event-Separation Properties of Event-Triggered Control Systems*, TAC 2014
[2] Donkers, H., *Output-Based Event-Triggered Control with Guaranteed L_∞-gain ...*, TAC 2012
[3] Tabuada, *Event-triggered real-time scheduling of stabilizing control tasks*, TAC 2007

ETC for disturbance / partial information case

Event generator
Relative $\lvert e\rvert \geqslant \sigma\lvert y\rvert$
Absolute $\lvert e\rvert \geqslant \delta$
Mixed $\lvert e\rvert \geqslant \sigma\lvert y\rvert + \delta$

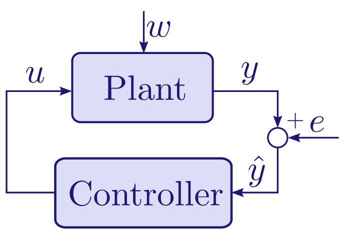
ETC for disturbance / partial information case

Event generator	non-Zenoness
Relative $\|e\| \geqslant \sigma\|y\|$	X
Absolute $\|e\| \geqslant \delta$	semi-global
Mixed $\|e\| \geqslant \sigma\|y\| + \delta$	semi-global

- Semi-global: lower bound on transmission interval depends on size of initial state (and goes to zero for large states)

ETC for disturbance / partial information case

Event generator	non-Zenoness	control properties
Relative $\|e\| \geqslant \sigma\|y\|$	X	X
Absolute $\|e\| \geqslant \delta$	semi-global	practical stability
Mixed $\|e\| \geqslant \sigma\|y\| + \delta$	semi-global	practical stability

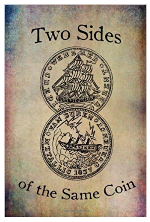


- Analysis can be found in [1,2]
- Use of absolute thresholds is partial solution
  - Semi-global strong non-Zenoness
  - No asymptotic stability ($x(t) \not\to 0$) and no finite $\mathcal{L}_2$-gain

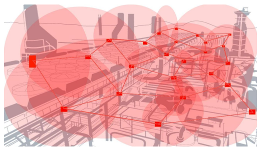
$$\|x\|_{\mathcal{L}_2} \leqslant \beta(|x(0)|) + \gamma\|w\|_{\mathcal{L}_2} \text{ with } \|x\|_{\mathcal{L}_2} = \sqrt{\int_0^\infty \|x(t)\|^2 dt}$$

[1] Borgers, H., *Event-Separation Properties of Event-Triggered Control Systems*, TAC 2014
[2] Donkers, H., *Output-Based Event-Triggered Control with Guaranteed L_∞-gain ...*, TAC 2012

Challenge for networked systems (with disturbances)








Challenge: What about global strong non-Zeno and GAS ($x(t) \to 0$) / finite $\mathcal{L}_2$-gains ?

TU/e

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Design for networked systems with disturbances

- Absolute triggering with time-varying threshold [0-2]

$$t_{k+1} = \min\{t \geqslant t_k \mid |y(t) - \hat{y}(t)| \geqslant \delta(t_k)\}$$

- Enforcing minimal inter-event/waiting time [3,6]

$$t_{k+1} = \min\{t \geqslant t_k + T \mid |y(t) - \hat{y}(t)| \geqslant \sigma |y(t)|\}$$

- Periodic Event-Triggered Control (PETC) [2-5]: Events only at kh, $k \in \mathbb{N}$

$$t_{k+1} = \min\{t > t_k \mid |y(t) - \hat{y}(t)| \geqslant \sigma |y(t)| \wedge t = kh,\ k \in \mathbb{N}\}$$

$\longrightarrow$ Combining the best of two worlds !?

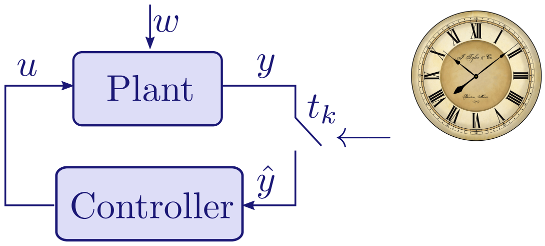
[0] Seyboth, Dimarogonas, Johansson, *Control of Multi-Agent Systems via Event-based Communication*, IFAC WC 2011
[1] Mazo Jr., Cao, *Asynchronous decentralized event-triggered control*, Automatica 2013
[2] Postoyan, Tabuada, Nešić, Anta, *Framework for the Event-Triggered Stabilization of Nonlinear Systems*, TAC15
[3] Heemels, Sandee, van den Bosch, *Analysis of event-driven controllers for linear systems*, IJC 2008
[4] Heemels, Donkers, Teel, *Periodic Event-Triggered Control for Linear Systems*, TAC 2013
[5] Henningsson, Johannesson, Cervin, *Sporadic event-based control of first-order linear stochastic ..*, Automatica 2008
[6] Tallapragada, Chopra, *Event-triggered decentralized dynamic output .. LTI systems*, NECSYS 2012

Outline

PETC for linear systems

Hybrid system formulation [0]

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}x &= A_p x + Bu + B_w w \\ y &= Cx \\ u &= K\hat{y} \end{aligned}$$



$$\xi = \begin{pmatrix} x \\ \hat{y} \end{pmatrix}$$

$$t_{k+1} = \min\{t > t_k \mid |y(t) - \hat{y}(t)| > \sigma|y(t)| \wedge t = kh,\ k \in \mathbb{N}\}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\xi \\ \tau\end{bmatrix} = \begin{bmatrix} A\xi + Bw \\ 1 \end{bmatrix}, \tau \in [0, h]$$

$$\begin{bmatrix}\xi^+ \\ \tau^+\end{bmatrix} = \begin{bmatrix} \phi(\xi) \\ 0 \end{bmatrix}, \qquad \tau = h$$

$$\phi(\xi) = \begin{cases} J_1\xi & \text{when } \xi^\top Q\xi > 0 \\ J_2\xi & \text{when } \xi^\top Q\xi \leqslant 0 \end{cases}$$

with $A := \begin{bmatrix} A_p & BK \\ 0 & 0 \end{bmatrix}$, $B := \begin{bmatrix} B_w \\ 0 \end{bmatrix}$, $J_1 := \begin{bmatrix} I & 0 \\ C & 0 \end{bmatrix}$, $J_2 := \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$

[0] Goebel, Sanfelice, Teel, *Hybrid dynamical systems: Modeling, Stability and Robustness*, 2012
[1] H., Dullerud, Teel, *$\mathcal{L}_2$-gain Analysis for a Class of Hybrid Systems with Applications to .. Event-triggered Control..*, TAC 2016
[2] H., Donkers, Teel, *Periodic Event-Triggered Control for Linear Systems*, TAC 2013

Periodic event-triggered control (PETC)

Discretization

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\xi \\ \tau\end{bmatrix} = \begin{bmatrix} A\xi + Bw \\ 1 \end{bmatrix}, \tau \in [0, h]$$

$$\begin{bmatrix}\xi^+ \\ \tau^+\end{bmatrix} = \begin{bmatrix} \phi(\xi) \\ 0 \end{bmatrix}, \qquad \tau = h$$

$$\phi(\xi) = \begin{cases} J_1\xi & \text{when } \xi^\top Q\xi > 0 \\ J_2\xi & \text{when } \xi^\top Q\xi \leqslant 0 \end{cases}$$

Discretization at sampling times kh, $k \in \mathbb{N}$, with $\xi_k = \xi(kh^+)$, when $(w = 0)$ leads to discrete-time piecewise linear system:

$$\xi_{k+1} = \phi(e^{Ah}\xi_k) = \begin{cases} J_1 e^{Ah}\xi_k, & \text{when } \xi_k^\top e^{A^\top h} Q e^{Ah}\xi_k > 0, \\ J_2 e^{Ah}\xi_k, & \text{when } \xi_k^\top e^{A^\top h} Q e^{Ah}\xi_k \leqslant 0 \end{cases}$$

- LMI-based analysis using piecewise quadratic Lyapunov functions [1,2]
- Also $\mathcal{L}_2$-gain analysis based on discrete-time PWL systems [3] (lifting)

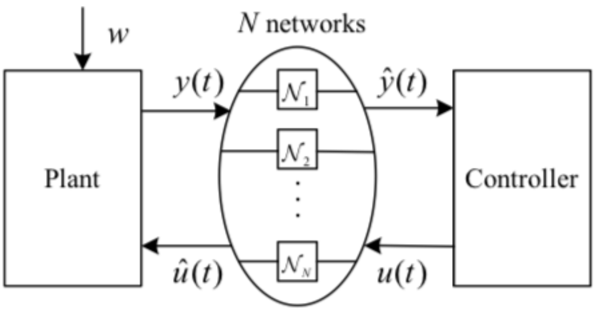
[1] Heemels, Donkers, Teel, *Periodic Event-Triggered Control for Linear Systems*, TAC 2013
[2] Heemels, Donkers, *Model-based Periodic Event-Triggered Control for Linear Systems*, Automatica 2013
[3] Heemels, Dullerud, Teel, *$\mathcal{L}_2$-gain Analysis for a Class of Hybrid Systems with Applications to .. Event-triggered Control*, TAC 2016

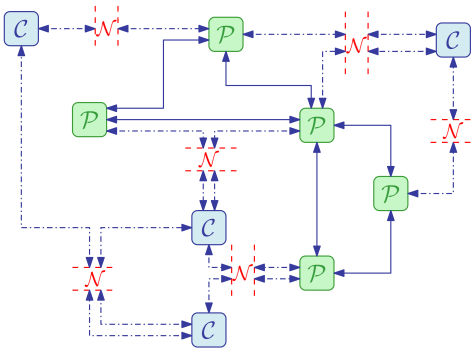
Outline

- Event-triggered control (ETC): Requirements
- Modelling systems with packet-based communication: hybrid systems
- Event generators:
  - Basic schemes (< 2012)
  - Challenges
  - Advanced schemes ($\geqslant 2012$)
  - Focus: Periodic event-triggered control
    - Stability and $\mathcal{L}_2$-gain analysis
    - Nonlinear distributed systems
    - Consistency: LQG
- Cooperative driving
- Conclusions

PETC: Interconnected nonlinear systems

- Asynchronous distributed PETC for nonlinear systems [1]
  - Network $\mathcal{N}_i$ has sampling times s_j^i with $s_{j+1}^i - s_j^i \leqslant T_i$
  - $t_{k+1}^i = \min\{t > t_k^i \mid \|y_i - \hat{y}_i\| > \sigma_i \|y_i\| \wedge t = s_j^i,\ j \in \mathbb{N}\}$





[1] Wang, R. Postoyan, D. Nesic, H., *Periodic event-triggered control for nonlinear networked control systems*, TAC 2020

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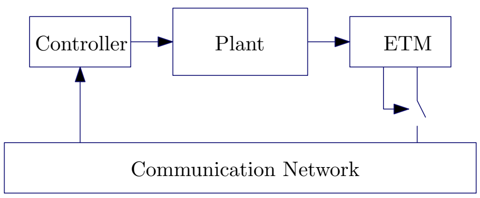
Is ETC better than TTC?

Consistency: [1] Better tradeoff between

- Quality of Control using some performance measure
- Cost of implementation (e.g. average transmission rate)



- LQG setting: Linear continuous-time plant $\dot{x} = Ax + Bu + w$
- Performance measure: $V_\pi := \limsup_{T\to\infty} \frac{1}{T}\mathbb{E}[\int_0^T x(t)^\mathsf{T} Qx(t) + u(t)^\mathsf{T} Ru(t)dt]$
- PETC controller/scheduler policy π:

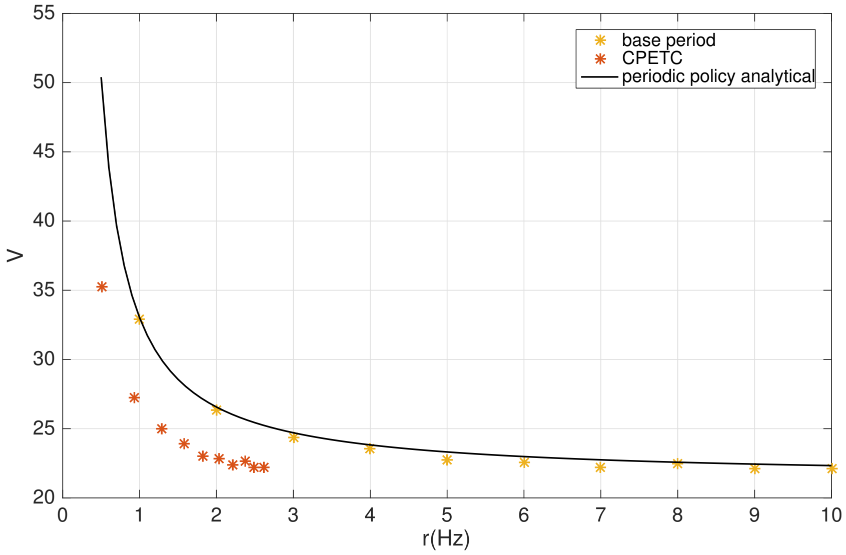
  checking at $s_k = kh$ to transmit ($\sigma_k = 1$) or not ($\sigma_k = 0$)
- Average transmission rate: $r_\pi := \frac{1}{h} \times \limsup_{N\to\infty} \frac{1}{N}\sum_{k=0}^{N-1}\mathbb{E}[\sigma_k]$

[1] Asadi Khashooei, Antunes, Heemels, *A Consistent Threshold-based Policy for Event-triggered Control*, IEEE Control Systems Letters 2018
[2] Antunes, Asadi Khashooei, *Consistent dynamic event-triggered policies for linear quadratic control*, CONES, 2017
[3] Antunes, Heemels, *Rollout event-triggered control: Beyond periodic performance*, TAC 14
[4] Astrom & Bernhardsson (IFAC WC 1999, CDC 2002)

Periodic event-triggered control (PETC)

- PETC outperforms time-triggered control in general LQG setting [1]:

Same cost $\lim_{T\to\infty} \frac{1}{T} \mathbb{E}[\int_0^T x(t)^\intercal Q x(t) + u(t)^\intercal R u(t) dt]$, lower average communication rate:



[1] Asadi Khashooei, Antunes, H., *A Consistent Threshold-based Policy for Event-triggered Control*, IEEE Control Systems Letters 2018

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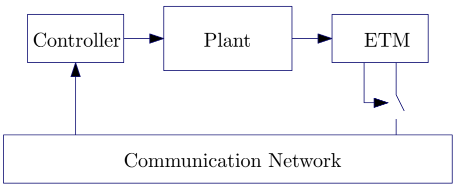
Consistent Event-triggered Control

Theorem: The following control/transmission policy is consistent:

- Model-based control-input generator (CIG) using the linear predictor



$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t), \quad t \neq s_k \text{ with } \sigma_k = 1 \\ \hat{x}(t) &= x(t), \quad t = s_k \text{ with } \sigma_k = 1 \\ u(t) &= K\hat{x}(t) \end{aligned}$$

- Scheduling policy (ETM):

$$\sigma_k = \begin{cases} 1, & \text{when } e_k^\intercal \Gamma e_k > \delta \\ 0, & \text{otherwise,} \end{cases}$$

where $e_k := e(s_k^-) = x(s_k^-) - \hat{x}(s_k^-)$, $s_k = kh$, $k \in \mathbb{N}$

- "I know what you know principle"

Asadi Khashooei, Antunes, H., *A Consistent Threshold-based Policy for Event-triggered Control*, IEEE Control Systems Letters 2018

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Design for networked systems with disturbances

- Periodic Event-Triggered Control (PETC) : Events only at kh, $k \in \mathbb{N}$

$$t_{k+1} = \min\{t > t_k \mid |y(t) - \hat{y}(t)| \geqslant \sigma |y(t)| \wedge t = kh, \ k \in \mathbb{N}\}$$

- Enforcing minimal inter-event/waiting time [1,2]

$$t_{k+1} = \min\{t \geqslant t_k + T \mid |\underbrace{y(t) - \hat{y}(t)}_{e(t)}| \geqslant \sigma |y(t)|\}$$

$t_{k+1} = \min\{t \geqslant t_k + T \mid \eta(t) \leqslant 0\}$ with local dynamic variable η given by

$$\dot{\eta} \sim \begin{cases} \Psi(e, y) \geqslant 0, & \text{when } t_k \leqslant t \leqslant t_k + T \\ -\beta\eta + \sigma^2|y|^2 - |e|^2, & \text{when } t_k + T \leqslant t \leqslant t_{k+1} \end{cases}$$

"low-pass filtered version of relative trigger $\sigma^2|y|^2 - |e|^2 \leqslant 0$"

[1] Dolk, Borgers, H., *Dynamic event-triggered control with time regularization ...*, IEEE Trans. Automatic Control 2017
[2] Dolk, Ploeg, H., *Event-triggered Control for String-Stable Vehicle Platooning*, IEEE Trans. Intell. Transp. Systems 2017

Cooperative Adaptive Cruise Control (CACC)

Movie event-triggered and time-triggered CACC [simulations]

Dolk, Ploeg, **H.**, *Event-triggered Control for String-Stable Vehicle Platooning*, IEEE Trans. Intell. Transp. Systems 2017

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Cooperative Adaptive Cruise Control (CACC)

Movie event-triggered and time-triggered CACC [real-life experiments]

- 75% savings in communication while virtually same performance

Dolk, Ploeg, **H.**, *Event-triggered Control for String-Stable Vehicle Platooning*, IEEE Trans. Intell. Transp. Systems 2017

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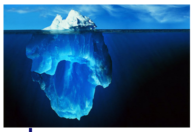
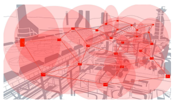
Conclusions



- Event-triggered control can obtain same quality of control with significant reduction of communication compared to time-triggered control

- Tip of the iceberg: Expanding field, still very much in motion:
  - Different system classes: stochastic systems, constrained systems (resource-aware MPC), discrete-time systems, distributed optimisation, ...
  - Different design approaches: delay-system approach, set-based approaches, optimal control approaches, learning-based approaches, self-triggered control, ...
  - Different aspects: quantization, (denial-of-service) attacks, packet losses, delays, etc.
- see www.heemels.tue.nl for preprints on these topics
- Future work: Building complete theory of ETC
  - Formal proofs ETC better than time-triggered (study of transmission intervals!)
  - Co-design of controller and event generators (for nonlinear systems)
  - Unification of the field
  - Multi-agent and distributed systems
  - Applications

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 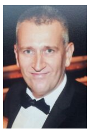    

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