Интегральное квадратичное разделение:
описание подхода, связь с функциями Ляпунова и S-процедурой Якубовича,
приложение к анализу устойчивости спутника с ограничением по входу

Dimitri PEAUCHELLE / Дмитрий Жанович Посель-Коновалов
LAAS-CNRS - Université de Toulouse - FRANCE

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Evaluating regions of attraction of LTI systems with saturation in IQS framework

Dimitri Peaucelle
Sophie Tarbouriech
Martine Ganet-Schoeller
Samir Bennani

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Introduction

- Saturated control of a linear system

\[ \dot{x} = Ax + Bu, \quad u = \text{sat}(Ky), \quad y = Cx \]

- Assume $K$ designed for the linear system (no saturation)

- System with saturation: Stability is (in general) only local

- Problem: find (largest possible) set of $x(0)$ such that $x(\infty) = 0$

- Goal of this presentation: formalize the problem in the IQS framework

- Can "system augmentation" relaxations provide less conservative results?
Well-posedness of a feedback loop

Uniqueness and boundedness of internal signals for all bounded disturbances

\[ \exists \gamma : \forall (\bar{w}, \bar{z}) \in L_2 \times L_2 , \left\| w - w_0 \right\| \leq \gamma \left\| \bar{w} \right\|, \left\| z - z_0 \right\| \leq \gamma \left\| \bar{z} \right\|, \]

with \( G(z_0, w_0) = 0 \)
\( F(w_0, z_0) = 0 \) solution to the system without perturbations
Well-posedness of a feedback loop

**Theorem:** Well-posed iff exists a topological separator $\theta$

- ‘Negative’ on the inverse graph of one component

$$G^I(\bar{w}) = \{(w, z) : G(z, w) = \bar{w}\} \subset \{(w, z) : \theta(w, z) \leq \phi_2(||\bar{w}||)\}$$

- ‘Positive definite’ on the graph of the other component of the loop

$$\mathcal{F}(\bar{z}) = \{(w, z) : F(w, z) = \bar{z}\} \subset \{(w, z) : \theta(w, z) > -\phi_1(||\bar{z}||)\}$$

**Issue 1:** How to choose $\theta$? **Answer:** S-procedure.

**Issue 2:** How to test the separation inequalities? **Answer:** LMIs.
Example: the small gain theorem

Well-posedness of a feedback loop

- In case of causal $G(z, w): w = \Delta z$, $\Delta \in \mathcal{RH}_\infty^{m \times l}$ and stable proper LTI $F(w, z): z = H(s)w$

- Necessary and sufficient (lossless) choice of separator

\[
\theta(w, z) = \|w\|^2 - \gamma^2\|z\|^2
\]

Separation inequalities:

\[
\theta(w, z) = \|w\|^2 - \gamma^2\|z\|^2 \leq 0, \quad \forall w = \Delta z \iff \|\Delta\|_\infty^2 \leq \gamma^2
\]

\[
\theta(w, z) = \|w\|^2 - \gamma^2\|z\|^2 > 0, \quad \forall z = H(s)w \iff \|H\|_\infty^2 < \frac{1}{\gamma^2}
\]
Example: stability of passive interconnected systems

**Well-posedness of a feedback loop**

- In case of passive $G(z, w): w = \Delta z$
- and stable LTI $F(w, z): z = H(s)w$

**Necessary and sufficient (lossless) choice of separator**

$$\theta(w, z) = - < w|z >$$

**Separation inequalities:**

$$\theta(w, z) = - < w|z > \leq 0, \forall w = \Delta z \iff \int_0^\infty w^T(t)z(t)dt \geq 0$$

$$\theta(w, z) = - < w|z > > 0, \forall z = H(s)w \iff H^*(j\omega) + H(j\omega) < 0, \forall \omega$$
Integral Quadratic Separation (IQS)

- From topological separation to IQS: Choice of an Integral Quadratic Separator

\[
\theta(w, z) = \left\langle \begin{pmatrix} z \\ w \end{pmatrix} \middle| \Theta \begin{pmatrix} z \\ w \end{pmatrix} \right\rangle = \int_0^\infty \begin{pmatrix} z^T(t) & w^T(t) \end{pmatrix} \Theta(t) \begin{pmatrix} z(t) \\ w(t) \end{pmatrix} dt
\]

- Identical choice to IQC framework [Megretski, Rantzer, Jönsson]

\[
\theta(w, z) = \int_{-\infty}^{+\infty} \begin{pmatrix} z^T(j\omega) & w^T(j\omega) \end{pmatrix} \Pi(j\omega) \begin{pmatrix} z(j\omega) \\ w(j\omega) \end{pmatrix} d\omega
\]

\(\Pi\) is called a multiplier. \(\theta(w, z) \leq 0\) is called an IQC.

- Conservatism reduction in IQC framework: \(\omega\)-dependent multipliers:

\[
\Pi(j\omega) = \left[ \begin{array}{c} 1 \\ \Psi_1(j\omega)^* \\ \vdots \\ \Psi_r(j\omega)^* \end{array} \right] \hat{\Pi}
\]
Main IQS result (both for $\omega$ or $t$ or $k$ dependent signals)

IQS is necessary and sufficient under assumptions (proof based on [Iwasaki 2001])

- One component is a linear application, can be descriptor form $F(w, z) = Aw - Ez$
- can be time-varying $A(t)w(t) - E(t)z(t)$ or frequency dep. $\hat{A}(\omega)\hat{w}(\omega) - \hat{E}(\omega)\hat{z}(\omega)$
- $A(t), E(t)$ are bounded and $E(t) = E_1(t)E_2$ where $E_1(t)$ is full column rank

- The other component can be defined in a set

$$G(z, w) = \nabla(z) - w, \quad \nabla \in \mathbb{W}$$

- $\mathbb{W}$ must have a linear-like property

$$\forall (z_1, z_2), \quad \forall \nabla \in \mathbb{W}, \quad \exists \tilde{\nabla} \in \mathbb{W}: \nabla(z_1) - \nabla(z_2) = \tilde{\nabla}(z_1 - z_2)$$

- $\mathbb{W}$ does not need to be causal

- The matrix $\Theta$ must satisfy an IQC over $\mathbb{W}$ + an LMI involving ($E, A$)
Global stability of a non-linear system $\dot{x} = f(x, t)$

$G(z, w) = \bar{w}$

$F(w, z) = \bar{z}$

$G(z = \dot{x}, w = x) = \int_{0}^{t} z(\tau) d\tau - w(t),$

$F(w, z, t) = f(w, t) - z(t)$

$\bar{w}$ plays the role of the initial conditions, $\bar{z}$ are external disturbances

Well-posedness: for all bounded initial conditions and all bounded disturbances,
the state remains bounded around the equilibrium $\equiv$ global stability
Global stability of a linear TV system $\dot{x} = A(t)x$

$G(z = \dot{x}, w = x) = \int_0^t z(\tau) d\tau - w(t) = s^{-1}z - w,$

$F(w, z, t) = A(t)w(t) - z(t)$

$\textbf{IQS}: \theta(w, z) = \int_0^\infty \left( \begin{array}{cc} z^T(t) & w^T(t) \end{array} \right) \left[ \begin{array}{cc} 0 & -P(t) \\ -P(t) & -\dot{P}(t) \end{array} \right] \left( \begin{array}{c} z(t) \\ w(t) \end{array} \right) dt$

$\theta(w, z) \leq 0 \text{ for all } G(z, w) = 0 \text{ iff } P(t) \geq 0$

$\left( x(0) = 0 , \int_0^t (\dot{x}^T P x + x^T \dot{P} x + x^T P \dot{x}) d\tau = x^T(t) P(t) x(t) \right)$

$\theta(w, z) > 0 \text{ for all } F(w, z) = 0 \text{ iff } A^T(t) P(t) + P(t) A(t) + \dot{P}(t) < 0$

$\left( z^T P w + w^T \dot{P} w + w^T P w = w^T (A^T P + PA + \dot{P}) w \right)$
Global stability of a system with a dead-zone

\[ G_1(\dot{x}, x) = \int_0^t \dot{x}(\tau) d\tau - x(t), \]
\[ G_2(g, v) = dz(g(t)) - v(t), \]
\[ F_1(x, v, \dot{x}, t) = f_1(x, v, t) - \dot{x}(t), \]
\[ F_2(x, v, g, t) = f_2(x, v, t) - g(t) \]

Dead-zone embedded in a sector uncertainty \( \mathcal{W}_\infty = \{ \nabla_\infty : 0 \leq \nabla_\infty(g) \leq g \} \)

\[ G_2^I = \{ (v, g) : G_2(g, v) = 0 \} \subset \{ (v, g) : v = \nabla_\infty(g), \nabla_\infty \in \mathcal{W}_\infty \} \]

Choosing \( \theta \) IQS w.r.t. \( \mathcal{W}_\infty \) rather than w.r.t. \( G_2^I \), is a source of conservatism
IQS applies for linear $f_1, f_2$

- Global stability of a system with a dead-zone

\[
G_1(\dot{x}, x) = \int_0^t \dot{x}(\tau) d\tau - x(t),
\]
\[
G_2(g, v) = dz(g(t)) - v(t),
\]
\[
F_1(x, v, \dot{x}, t) = Ax(t) + Bu(t) - \dot{x}(t),
\]
\[
F_2(x, v, g, t) = Cx(t) + Du(t) - g(t)
\]

- LMI conditions obtained for the IQS defined by

\[
\Theta = \begin{bmatrix}
0 & 0 & -P & 0 \\
0 & 0 & 0 & -p_1 \\
-P & 0 & 0 & 0 \\
0 & -p_1 & 0 & 2p_1 \\
\end{bmatrix}, \quad P > 0,
\]
\[
p_1 > 0.
\]

- Result is exactly identical to circle theorem result
Launcher model

Launcher in ballistic phase: attitude control

Neglected atmospheric friction, sloshing modes, ext. perturbation, axes coupling: $I\ddot{\theta} = T$

Saturated actuator: $T = \text{sat}_T(u) = u - \bar{T}dz(\frac{1}{T}u)$

PD control $u = -K_P\theta - K_D\dot{\theta}$

\[
G_1(\dot{x}, x) = \int_0^t \dot{x}(\tau) d\tau - x(t),
\]

\[
G_2(g, v) = dz(g(t)) - v(t),
\]

\[
F_1(x, v, \dot{x}, t) = \begin{bmatrix} 0 & 1 \\ -K_P & -K_D \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ -\bar{T} \end{bmatrix} v(t) - \dot{x}(t),
\]

\[
F_2(x, v, g, t) = \begin{bmatrix} -\frac{K_P}{T} & -\frac{K_D}{T} \end{bmatrix} x(t) - g(t)
\]
Global stability LMI test fails

- Sector uncertainty $\mathcal{W}_\infty$ includes $\nabla_\infty = 1$ for which the system is $I\ddot{\theta} = 0$ (unstable)

LMI test succeeds (whatever $\bar{g} < \infty$) if dead-zone is restricted to belong to

$$\mathcal{W}_{\bar{g}} = \{ \nabla_{\bar{g}} : 0 \leq \nabla_{\bar{g}}(g) \leq \frac{1-\bar{g}}{\bar{g}} g \}$$

Useful if one can prove for constrained $x(0)$ that $|g(\theta)| \leq \bar{g}$ holds $\forall \theta \geq 0$.

How can one prove local properties in IQS framework?
Initial conditions dependent IQS

- Well-posedness of a feedback loop

\[
\begin{align*}
G(z, w) &= \bar{w} \\
F(w, z) &= \bar{z}
\end{align*}
\]

- Uniqueness and boundedness of internal signals for all bounded disturbances

\[
\exists \gamma : \forall (\bar{w}, \bar{z}) \in L_2 \times L_2 , \quad \left\| w - w_0 \right\| \leq \gamma \left\| \bar{w} \right\|, \quad G(z_0, w_0) = 0 \quad F(w_0, z_0) = 0
\]

- How to introduce initial conditions \( x(0) \) and "final" conditions \( g(\theta) \) in IQS framework?

- Square-root of the Dirac operator: linear operator such that

\[
\begin{align*}
\langle \varphi_{\theta_1} x | M \varphi_{\theta_2} x \rangle &= \int_0^\infty \varphi_{\theta_1} x^T(t) M \varphi_{\theta_2} x(t) dt = x^T(\theta) M x(\theta) \\
\langle \varphi_{\theta_1} x | M \varphi_{\theta_2} x \rangle &= 0 \text{ if } \theta_1 \neq \theta_2
\end{align*}
\]

- Such operator is also used for PDE to describe states on the boundary
System with initial and final conditions writes as

\[
\begin{pmatrix}
\varphi_0 x \\
T_\theta \dot{x} \\
T_\theta g \\
\varphi_\theta g
\end{pmatrix}
= \begin{bmatrix}
0 & 0 & 0 & 1 \\
A & 0 & B & 0 \\
C & 0 & 0 & 0 \\
0 & C & 0 & 0
\end{bmatrix}
\begin{pmatrix}
T_\theta x \\
\varphi_\theta x \\
T_\theta v \\
\varphi_0 x
\end{pmatrix}
\]

$T_\theta x$ is the truncated signal such that $T_\theta x(t) = x(t)$ for $t \leq \theta$ and $= 0$ for $t > \theta$.

The integration operator is redefined as a mapping

\[
\begin{pmatrix}
T_\theta x \\
\varphi_\theta x
\end{pmatrix}
= \mathcal{I}
\begin{pmatrix}
\varphi_0 x \\
T_\theta \dot{x}
\end{pmatrix}
\]
Initial conditions dependent IQS

\[
\begin{pmatrix}
\varphi_0 x \\
\mathcal{T}_\theta x \\
\mathcal{T}_\theta g \\
\varphi_0 g \\
\end{pmatrix}
= 
\begin{pmatrix}
0 & 0 & 0 & 1 \\
A & 0 & B & 0 \\
C & 0 & 0 & 0 \\
0 & C & 0 & 0 \\
\end{pmatrix}
\begin{pmatrix}
\mathcal{T}_\theta x \\
\varphi_0 x \\
\mathcal{T}_\theta v \\
\varphi_0 v \\
\end{pmatrix}
\]

*Restricted sector constraint assumed to hold up to \( t = \theta \):

\[
\mathcal{T}_\theta v = \nabla_{\vec{g}} \mathcal{T}_\theta g
\]
Initial conditions dependent IQS

\[
\begin{bmatrix}
\varphi_0 x \\
\mathcal{T}_\theta \dot{x} \\
\mathcal{T}_\theta g \\
\varphi_\theta g
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 1 \\
A & 0 & B & 0 \\
C & 0 & 0 & 0 \\
0 & C & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\mathcal{T}_\theta x \\
\varphi_\theta x \\
\mathcal{T}_\theta v \\
\varphi_0 x
\end{bmatrix}
\]

Goal is to prove the restricted sector condition holds strictly at time \( \theta \) (whatever \( \theta \)).

i.e. find sets \( 1 \geq x^T(0)Qx(0) = <\varphi_0 x|Q\varphi_0 x > \) s.t. \( |g(\theta)| = \|\varphi_\theta g\| < \bar{g} \)

reformulated as well posedness problem where \( \varphi_0 x = \nabla_{ci} \varphi_\theta g \) defined by

\[
w_{ci} = \nabla_{ci} z_{zi} : \quad \bar{g}^2 < w_{ci} |Qw_{ci} > \leq \|z_{ci}\|^2
\]

\( \nabla_{ci} \) is a non-causal, virtual, operator, used to define the problem in IQS framework.
Initial conditions dependent IQS

\[
\begin{pmatrix}
\varphi_0 x \\
\mathcal{T}_\theta \dot{x} \\
\tau x \\
\varphi_\theta g
\end{pmatrix}
= 
\begin{bmatrix}
0 & 0 & 0 & 1 \\
A & 0 & B & 0 \\
C & 0 & 0 & 0 \\
0 & C & 0 & 0
\end{bmatrix}
\begin{pmatrix}
\mathcal{T}_\theta x \\
\varphi_\theta x \\
\tau x \\
\varphi_0 x
\end{pmatrix}
\]

Problem defined in this way is a well-posedness problem with $\nabla$ composed of 3 blocs

\[
\nabla = 
\begin{bmatrix}
I & 0 \\
\nabla \bar{g} \\
0 & \nabla_{ci}
\end{bmatrix}
\]

IQS framework applies and gives conservative LMI conditions

Equivalent to LaSalle invariance principle with $V(x) = x^T Q x$ (ellipsoidal sets of IC)
How to reduce conservatism?

- Needed a description of the dead-zone better than sector uncertainty
- Needed to have dead-zone dependent sets of initial conditions

Both features derived via descriptor modeling of system augmented with $\dot{v}$ and $\dot{g}$

$$v = dz(g) : \begin{cases} 
\text{if } g > 1 & v = g - 1, \dot{v} = \dot{g} \\
\text{if } |g| \geq 1 & v = 0, \dot{v} = 0 \\
\text{if } g < -1 & v = g + 1, \dot{v} = \dot{g} 
\end{cases}$$

- For IQS, link between $\dot{v}$ and $\dot{g}$ is embedded in $\dot{v} = \nabla_{\{0,1\}} \dot{g}$, with $\nabla_{\{0,1\}} \in \{0, 1\}$.
- Also needed to specify that $v$ is the integral of $\dot{v}$ (thus descriptor form)
System augmentation with derivatives

- All system equations:

\[
\begin{align*}
T_\theta \dot{x} &= AT_\theta x + BT_\theta v \\
T_\theta g &= CT_\theta x \\
T_\theta \dot{g} &= CT_\theta \dot{x} \\
\varphi_\theta g &= C\varphi_\theta x
\end{align*}
\]

\[
\begin{bmatrix}
T_\theta x \\
T_\theta v \\
\varphi_\theta x \\
\varphi_\theta v
\end{bmatrix}
= I
\]

\[
\begin{bmatrix}
\varphi_0 x \\
\varphi_0 v \\
T_\theta \dot{x} \\
T_\theta \dot{g}
\end{bmatrix}
= \nabla_{\gamma} T_\theta g
\]

\[
\begin{bmatrix}
\varphi_0 x \\
\varphi_0 v
\end{bmatrix}
= \nabla_{\gamma} \varphi_\theta g
\]

\[
\begin{bmatrix}
T_\theta v = \nabla_{\gamma} T_\theta \dot{g} \\
\varphi_\theta v = \nabla_{\gamma} \varphi_\theta \dot{g}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\varphi_0 x \\
\varphi_0 v
\end{bmatrix}
= \nabla_{ci} \varphi_\theta g
\]

- Gives a descriptor matrix linear transformation

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\varphi_0 x \\
\varphi_0 v \\
T_\theta \dot{x} \\
T_\theta \dot{g} \\
\varphi_\theta g \\
\varphi_\theta \dot{g}
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
T_\theta x \\
T_\theta v \\
\varphi_\theta x \\
\varphi_\theta v \\
T_\theta \dot{x} \\
T_\theta \dot{g} \\
\varphi_\theta g \\
\varphi_\theta \dot{g}
\end{bmatrix}
\]

- Problem defined in this way is a well-posedness problem with \(\nabla\) composed of 5 blocs
IQS framework applies and gives less conservative LMI conditions

Equivalent to LaSalle invariance principle with

\[ V(x) = \begin{pmatrix} x \\ v \end{pmatrix}^T Q_a \begin{pmatrix} x \\ v \end{pmatrix} = \begin{pmatrix} x \\ \text{d}z(Cx) \end{pmatrix}^T Q_a \begin{pmatrix} x \\ \text{d}z(Cx) \end{pmatrix} \]

Such result cannot be obtained when applying classical IQC results
Application to the launcher model

**LMIs tested on the launcher example**

- Sets of initial conditions for which $|g(\theta)| \leq 8$ is guaranteed
- Improvement thanks to piecewise quadratic sets of initial conditions
Conclusions

- IQS framework can handle local stability issues
- Provides LMI tests - conservative
- System augmentation + descriptor modeling = reduction of conservatism

Prospectives
- Improved construction of the IQS ≡ “generalized sector conditions”
- Further system augmentation with higher derivatives (?)
- Simultaneous handling of saturation, uncertainties, delays...
- Hybrid systems ?