Robust techniques of automatic control for mobile robotic systems

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Plan

1. Introduction.
2. AUV Ciscrea modeling.
3. Input constraint compensating algorithm.
4. Output constraint compensating algorithm.
5. Control design under structural constraints.
6. Control design under dynamic constraints.
7. Concluding remarks.

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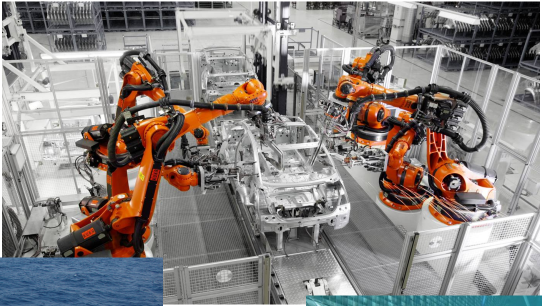
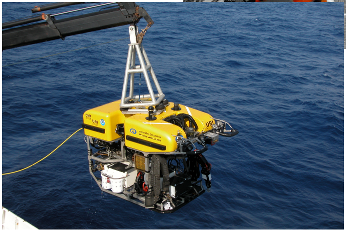
Robots.

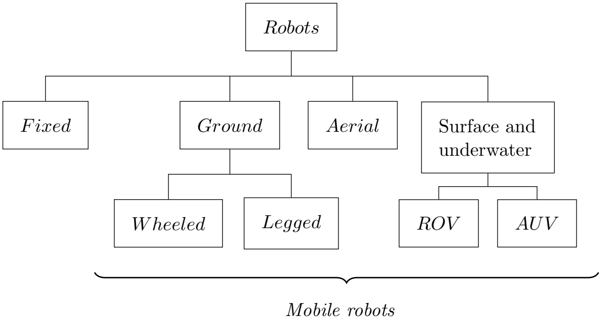




Types of Robots.

From the mechanical point of view:

- Fixed robots.
- Mobile robots.



Fields of application.

Considering their potential use and the degree of technologies development:

- Industrial robotics.

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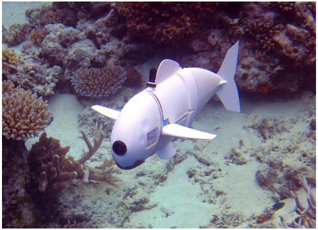
- Industrial robotics.
- Advanced robotics.



About this work.

This thesis focuses on:

- Mobile robot control.
- Advanced robot applications.

In particular it will be focused on the control objectives of:

- Tracking task.
- Obstacle avoidance task.

About this work

The control of these systems is strongly affected by:

- Constraint effects.
- Non idealities.
- External perturbations.

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The control of these systems is strongly affected by:

- Constraint effects.
- Non idealities.
- External perturbations.

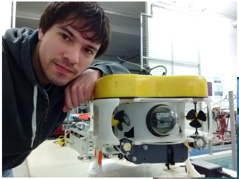
To deal with these problems the following is proposed:

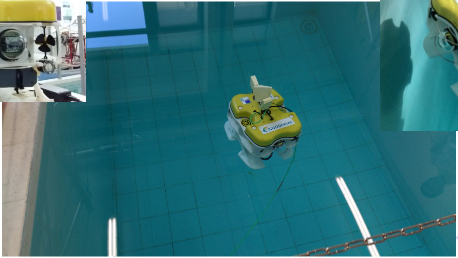
1. External loops to the main control of these systems in order to reduce the input/output constraint effects.
2. A robust controller tuning technique considering structural constraints.
3. Controllers synthesis and analysis considering non-idealities and dynamic constraints.

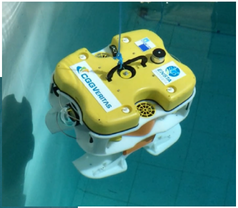
Plan

AUV Ciscrea

Size	0.525m (L) 0.406m (W) 0.395m (H)
Weight in air	15.56kg (without payload and floats)
Degrees of Freedom	Surge, Sway, Heave and Yaw
Propulsion	2 vertical and 4 horizontal propellers
Speed	2 knots (Surge) and 1 knot (Sway, Heave)
Depth Rating	50m
On-board Battery	2-4 hours







AUV Ciscrea model

Rigid-body dynamic:

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu = \tau_{env} + \tau_{hydro} + \tau_{pro} \quad (1)$$

Hydrodynamic formulations:

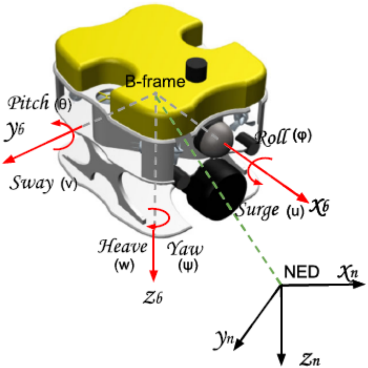
$$\tau_{hydro} = -M_A\dot{\nu} - C_A(\nu)\nu - D(|\nu|)\nu - g(\eta) \quad (2)$$

Damping:

$$D(|\nu|) = D_L + D_N|\nu| \quad (3)$$

Parameter	Description
M_{RB}	AUV rigid-body mass and inertia matrix
M_A	Added mass matrix
C_{RB}	Rigid-body induced coriolis-centripetal matrix
C_A	Added mass induced coriolis-centripetal matrix
$D(\|\nu\|)$	Damping matrix
$g(\eta)$	Restoring forces and moments vector
τ_{env}	Environmental disturbances(wind,waves and currents)
τ_{hydro}	Vector of hydrodynamic forces and moments
τ_{pro}	Propeller forces and moments vector

AUV Ciscrea model



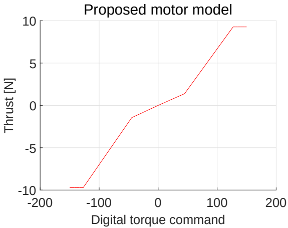
1. 6 degrees of freedom.
2. 4 degrees controllable.

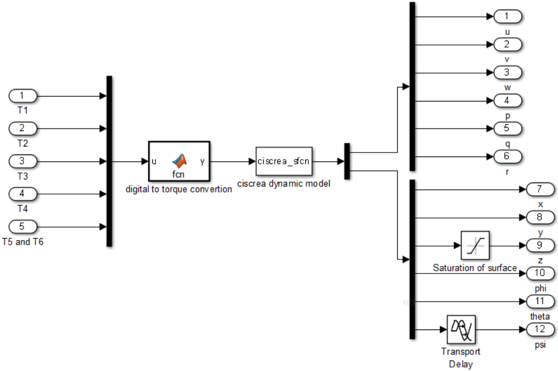
AUV Ciscrea model

$$\left\{ M_A + \begin{pmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_x & 0 & 0 \\ 0 & 0 & 0 & 0 & I_j & 0 \\ 0 & 0 & 0 & 0 & 0 & I_k \end{pmatrix} \right\} \begin{pmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{n} [T_i \cos(\psi_{t_i}) \cos(\theta_{t_i})] - (m - \rho v_{ol}) g \sin(\theta) - D_{Nu}|u|u + D_{Lu}u + m(rv - qw) \\ \sum_{i=1}^{n} [T_i \sin(\psi_{t_i}) \cos(\theta_{t_i})] + (m - \rho v_{ol}) g \cos(\theta) \sin(\phi) + D_{Nv}|v|v + D_{Lv}v + m(pw - ru) \\ -\sum_{i=1}^{n} [T_i \sin(\theta_{t_i})] + (m - \rho v_{ol}) g \cos(\theta) \cos(\phi) - D_{Nw}|w|w + D_{Lw}w + m(qu - pv) \\ -\sum_{i=1}^{n} \left[T_i \left(y_{t_i} \sin(\theta_{t_i}) + z_{t_i} \sin(\psi_{t_i}) \cos(\theta_{t_i})\right)\right] - D_{Np}|p|p + D_{Lp}p + (I_y - I_z)qr \\ \sum_{i=1}^{n} \left[T_i \left(z_{t_i} \cos(\psi_{t_i}) \cos(\theta_{t_i}) + x_{t_i} \sin(\theta_{t_i})\right)\right] - D_{Nq}|q|q + D_{Lq}q + (I_z - I_x)rp \\ \sum_{i=1}^{n} \left[T_i \left(x_{t_i} \sin(\psi_{t_i}) \cos(\theta_{t_i}) - y_{t_i} \cos(\psi_{t_i}) \cos(\theta_{t_i})\right)\right] - D_{Nr}|r|r + D_{Lr}r + (I_x - I_y)pq \end{pmatrix} \quad (4)$$

1. Position of each propeller is considered.
2. Cross relations between equations due to the angular momentum are considered.

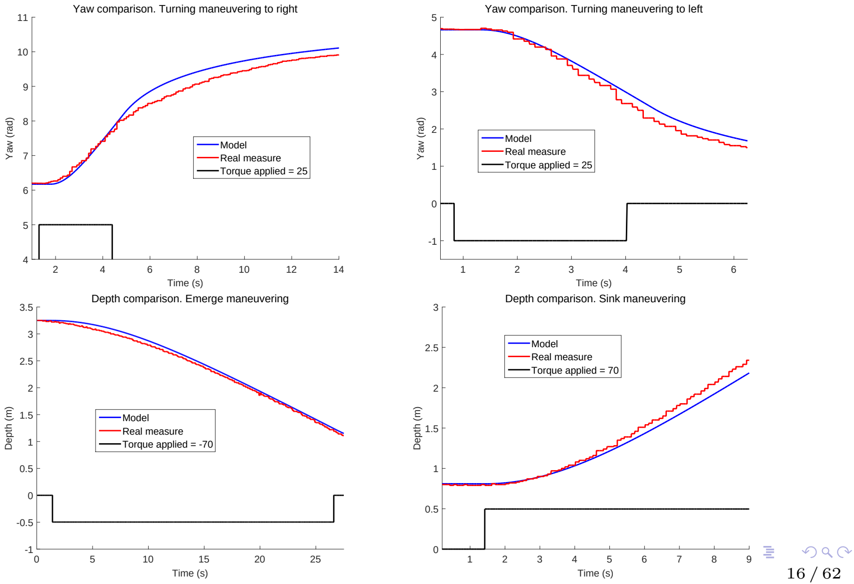
Simulator





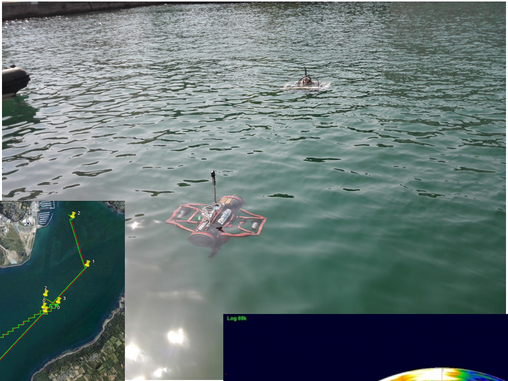
1. Conversion of torque value.
2. Delay in the Yaw measure.

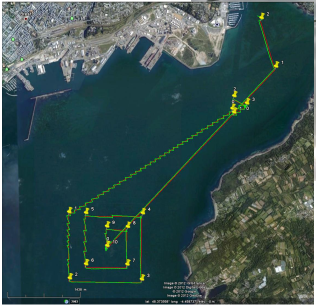
Model validation

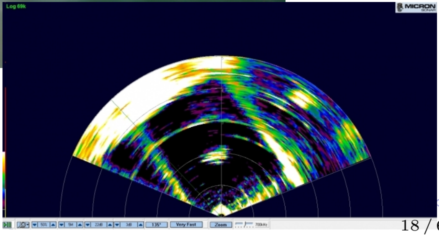


Plan

Case study: Ciscrea AUV path following.







Issues.

In most of the cases:

1. Path to follow is given as vector input that can be parametrized in terms of a motion parameter.

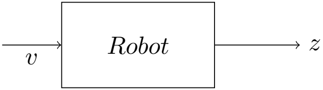
The objective:

1. Bounded path error.
2. Minimal execution time.

The problems:

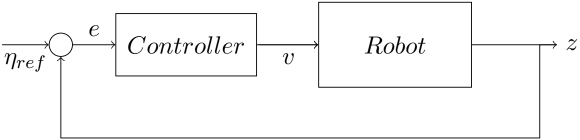
1. Saturation of actuators.
2. Regulation of the speed reference.

Sliding mode motion parameter adaption (SMMPA).



1. Modeling.

Sliding mode motion parameter adaption (SMMPA).



1. Modeling.
2. Classic feedback control.

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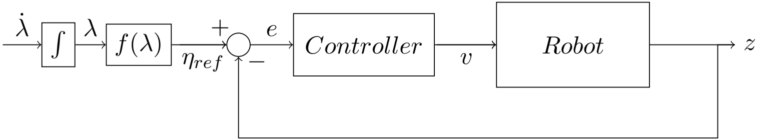
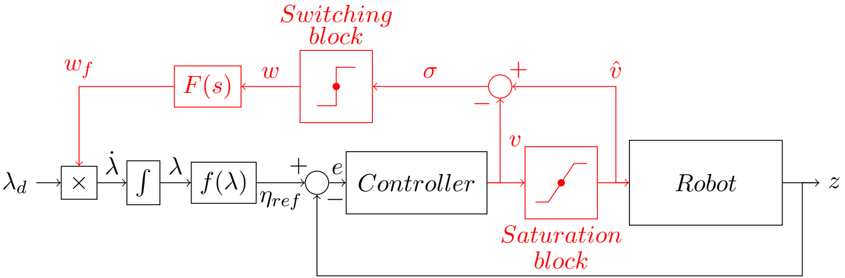


1. Modeling.
2. Classic feedback control.
3. Reference parametrization.

Sliding mode motion parameter adaption (SMMPA).



1. $F(s)$: First order low pass filter.
2. λ_d : Reference speed parameter.
3. $f(\lambda)$: Parametrization of the path.
4. *Controller* : PD controller.

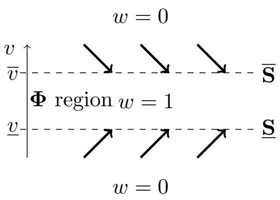
Sliding mode motion parameter adaption (SMMPA).

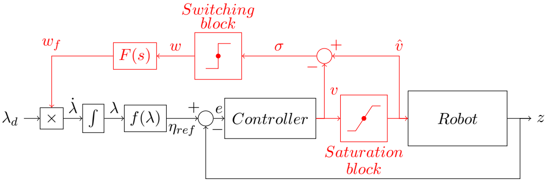
1. Switching law:

$$w = \begin{cases} 1 & if \quad \sigma = 0 \\ 0 & if \quad \sigma \neq 0 \end{cases} \qquad (5)$$

With:

$$\sigma(v) = v - \tilde{v} \qquad (6)$$





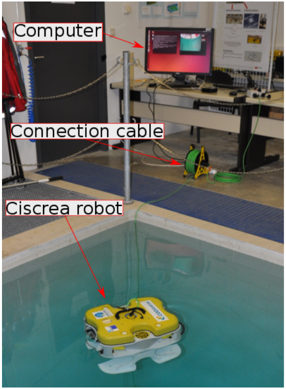
Experimental setup.

Two situations are proposed:

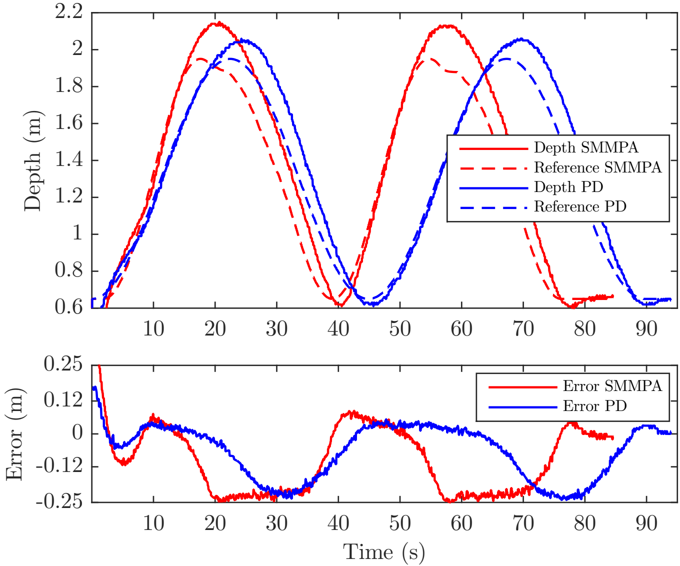
1. PD controller tuned to avoid actuator saturation.
2. The previous PD controller plus the proposed loop. Tuned so as to have the same order of path error.

Parameter values:

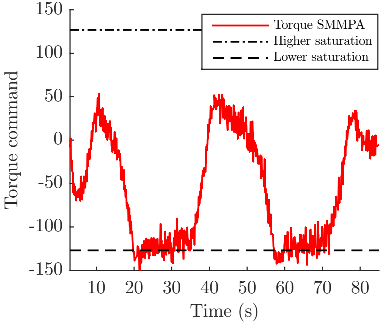
1. $\lambda_d = 0.2$
2. Cutoff frequency of the low pass filter $f_c = 0.2387 H_z$
3. PD controller: $K_p = 541.43$, $K_d = 250$, and $f_f = 2.3 H_z$
4. Step time: 0.1 seconds

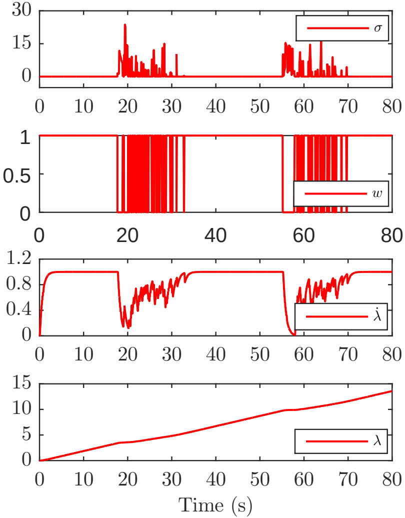


Experimental results - Path following comparison.



Experimental results - Loop signals.





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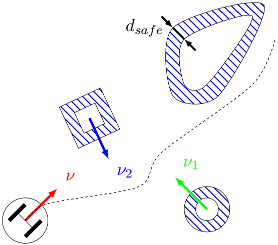
Case study: strict path following.

Objectives:

1. To follow a restricted path with minimum error in an unknown environment.
2. Minimal execution time.
3. Obstacle avoidance considering maximum dynamics that the vehicle must respect.

Problem description

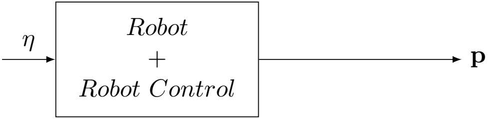


Given:

1. Ψ subset of the environment that contains the obstacles.
2. $\hat{\Psi}$ extension of the subset Ψ that considers the safety margin d_{safe}.
3. $d(t)$ minimum distance from the robot to the subset Ψ.

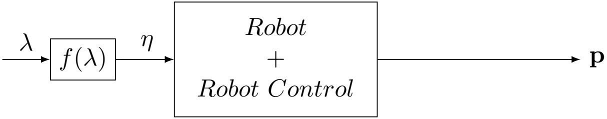
$$d(t) := \min_{\mathbf{r}\in\Psi} \| \mathbf{r} - \mathbf{p}(t) \| \tag{7}$$

Collision avoidance speed adaption (CASA)



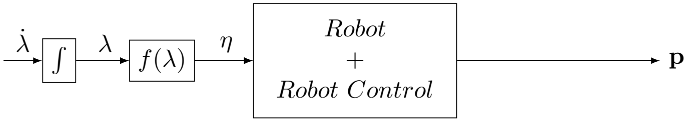
1. Robot.

Collision avoidance speed adaption (CASA)



1. Robot.
2. Path parametrization.

Collision avoidance speed adaption (CASA)



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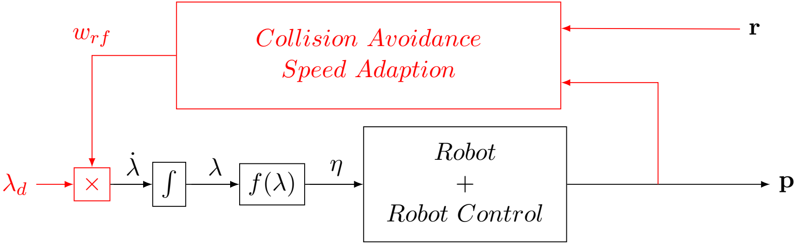
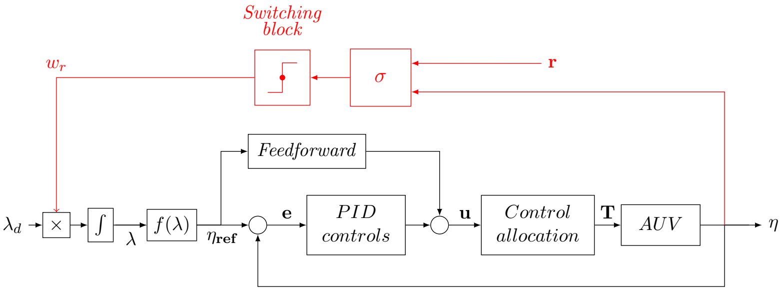


1. Robot.
2. Path parametrization.
3. Obstacle avoidance algorithm.

Implementation in AUV Ciscrea.



1. Minimal distance

$$d(t) := \min_{\mathbf{r}\in\Psi} \parallel \mathbf{r} - \eta(t) \parallel$$

2. Sliding function

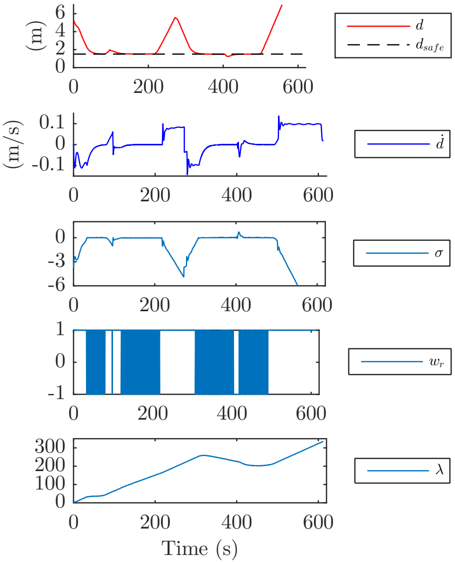
$$\sigma = d_{safe} - k_d d - k_{dd}\dot{d}$$

3. Switching function

$$w_r = \begin{cases} 1 & \sigma \leq 0 \\ -1 & \sigma > 0 \end{cases}$$

Implementation in AUV Ciscrea - simulations.

Implementation in AUV Ciscrea - Loop signals.



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Structural constraints.

- The performance of the previous auxiliary-loop techniques relies on the tune of a main controller.
- The controller is frequently predefined in industrial or commercial robots.

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Proposal:

- To tune a PID structured controller from H_∞ specification.
- A global optimization approach which enables performing a robustness analysis in a guaranteed way based on Interval Analysis.

Robustness analysis.

1. Let $G(\sigma)$ be a LTI system which depends on real uncertain parameters $\sigma \in \Sigma$, where Σ denotes the set of admissible value of uncertainties.
2. Suppose that a controller K was synthesized for a nominal plant $G(\sigma_n)$ from constraints of the kind $\mathcal{C}(G, K) \leq 0$. Remembering:
    - The stability constraint: $R_i(\sigma) \leq 0$ using the Routh-Hurwitz criterion.
    - The H_∞ constraints can be formulated as the modulus of a transfer function T, $|T(\sigma, i\omega)| - 1 \leq 0$.

Robustness analysis.

The proposed robustness analysis consists in verifying that the constraints are respected for all uncertainty values:

$$\text{Prove that } \mathcal{C}(G(\sigma), K) \leq 0,\ \forall \sigma \in \Sigma \tag{8}$$

[1] Monnet, D et al. (2016) A global optimization approach to structured regulation design under H_∞ constraints.

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$$\text{Prove that } \mathcal{C}(G(\sigma), K) \leq 0, \ \forall \sigma \in \Sigma \tag{8}$$

As these constraints are not convex with structured controllers $\Rightarrow$ a global optimization approach based on interval arithmetic is used[1]:

$$\sup_{\sigma \in \Sigma, \omega \in \Omega} \mathcal{C}(G(\sigma, i\omega), K(i\omega)) \tag{9}$$

where Ω is a bounded interval of $\mathbb{R}^+$

[1] Monnet, D et al. (2016) A global optimization approach to structured regulation design under H_∞ constraints.

Case study: AUV Ciscrea yaw direction control.

A linear system is needed:

1. Dismissing coupling effects between directions.
2. Linearizing the non-linear system, the non-linear behavior of actuators and the compass delay.

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1. Dismissing coupling effects between directions.
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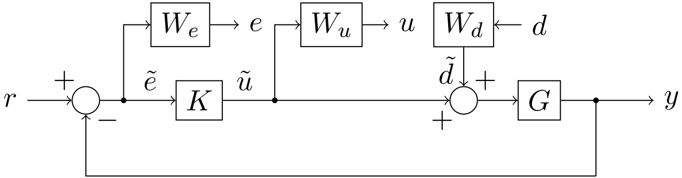
The Yaw dynamic can be represented by the transfer function:

$$\frac{\psi(s)}{r(s)} = \frac{0.3931}{s^2 + 2.08\delta s} \frac{1 - 0.25s}{1 + 0.25s} \tag{10}$$

where δ is the yaw angular velocity at which the system is linearized.

Control design objectives.



These lead to the following synthesis problem, where if the norms are under 1, then the specifications are guaranteed.

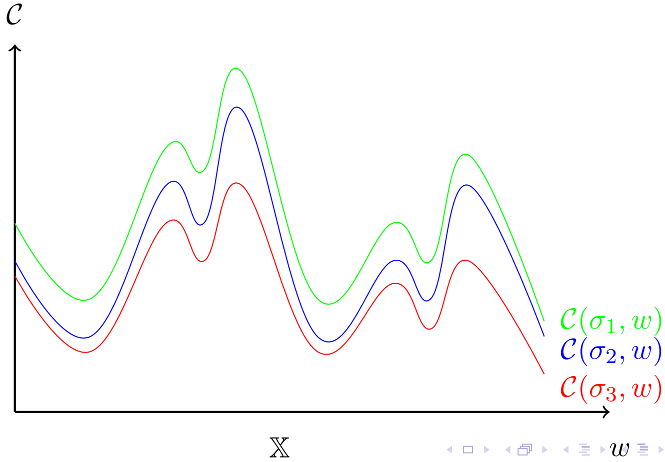
$$\text{Find } K \text{ such as } \alpha \text{ is minimum}$$
$$\begin{cases} \|W_e T_{r\to\tilde{e}}\|_\infty \leq \alpha, \\ \|W_e T_{\tilde{d}\to\tilde{e}} W_d\|_\infty \leq \alpha, \\ \|W_u T_{r\to\tilde{u}}\|_\infty \leq \alpha, \\ K \text{stabilizes the closed-loop system.} \end{cases} \tag{11}$$

with

$$W_e(s) = \frac{0.1s+0.6283}{s+0.06283}, \quad W_d(s) = \frac{0.1s+0.06283}{s+0.6283}, \quad W_u = 0.167.$$

Interval arithmetic & interval branch and bound algorithm (IBBA).

$$\sup_{\sigma\in\Sigma,\omega\in\Omega} \mathcal{C}(G(\sigma, i\omega), K(i\omega))$$



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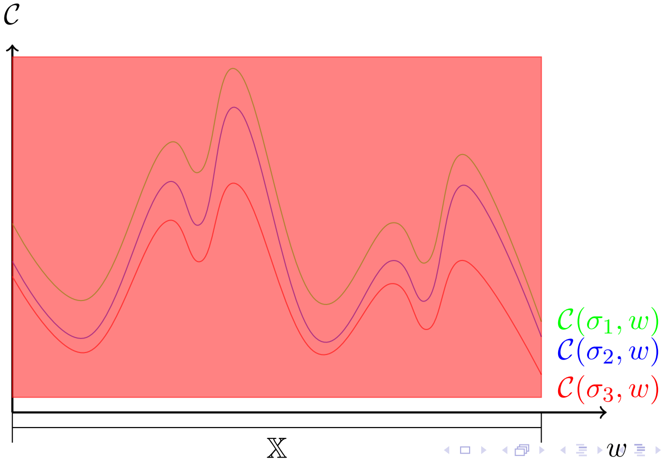

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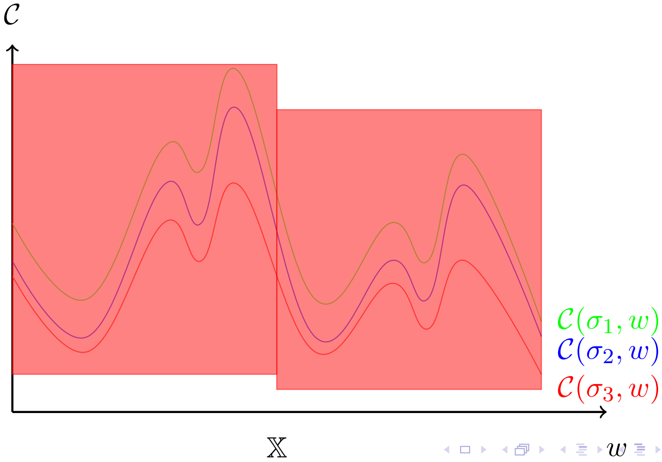

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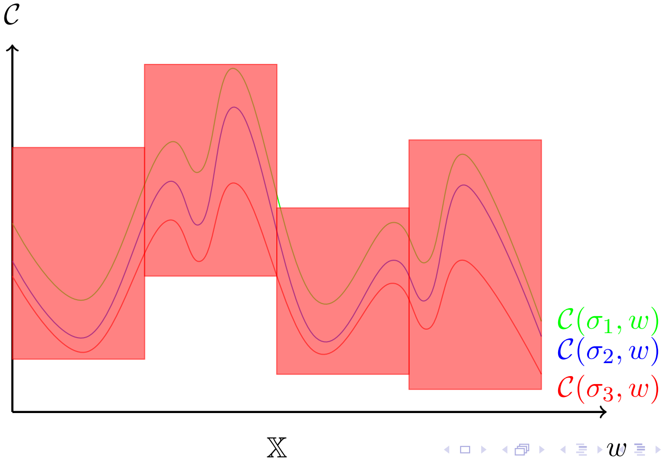

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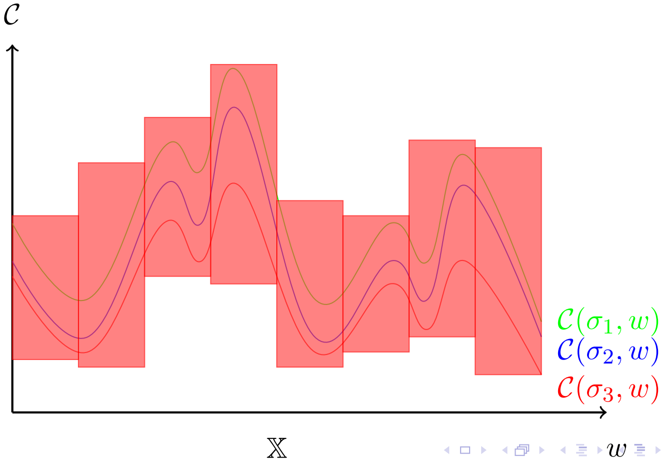

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Interval arithmetic & interval branch and bound algorithm (IBBA).

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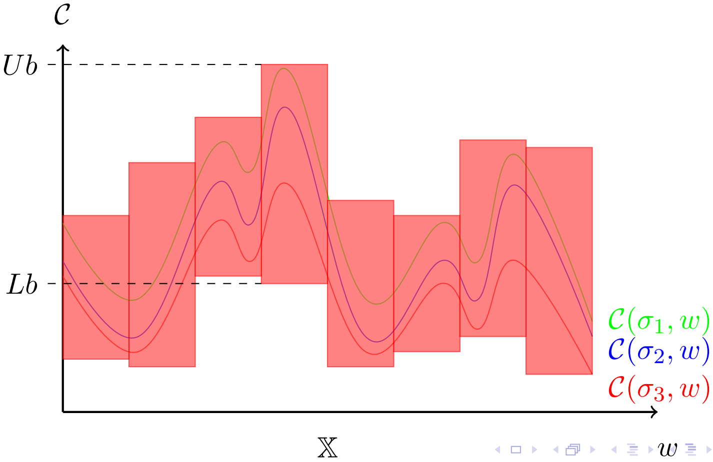


Control design.

- We propose to synthesize a PID controller with a particular plant $G(\tilde{\delta})$, with $\delta = \tilde{\delta} = 2$.
- The PID controller has the form: $K(k,s) = k_p + \frac{k_i}{s} + \frac{k_d s}{1+Ts}$ with $k = (k_p, k_i, k_d, T)$.
- The Matlab's toolbox Systune provides the following solution:

$$\tilde{k} = (4.68, 0.71, 4.68, 0.11).$$

- The control law is robust if both stability and H_∞ constraints are respected for all $\delta \in [0,4]$.

Analysis results.

The stability of the closed-loop system can be expressed as a set of four polynomial inequalities with the Routh-Hurwtiz criterion:

$$\sup_{\delta\in[0,4]} R_i(\delta,\tilde{k}) \leq -0.01, \forall i \in \{1,...,4\},$$

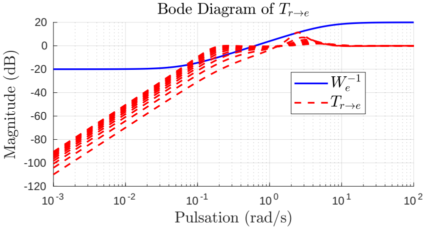
This proves that $K(\tilde{k})$ robustly stabilizes the linear closed-loop system.

The robustness analysis of H_∞ constraints over the pulsation range $[0,\omega_c]$ provides the following results:

$$\sup_{\delta\in[0,4]} \{\|W_e T_{r\to\tilde{e}}(\tilde{k})\|_\infty\} \in [6.55, 7.20]$$

$$\sup_{\delta\in[0,4]} \{\|W_e T_{d\to\tilde{e}}(\tilde{k}) W_d\|_\infty\} \leq 0.56$$

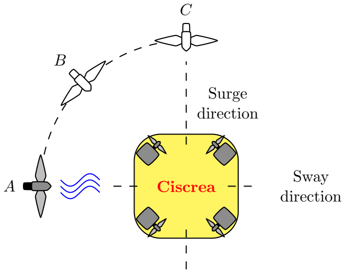
$$\sup_{\delta\in[0,4]} \{\|W_u T_{r\to\tilde{u}}(\tilde{k})\|_\infty\} \leq 0.89$$

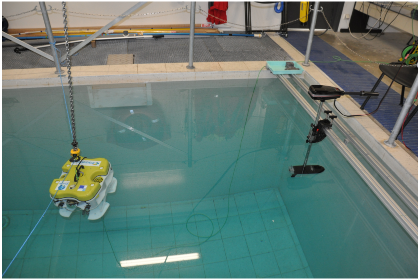


Experiment setup

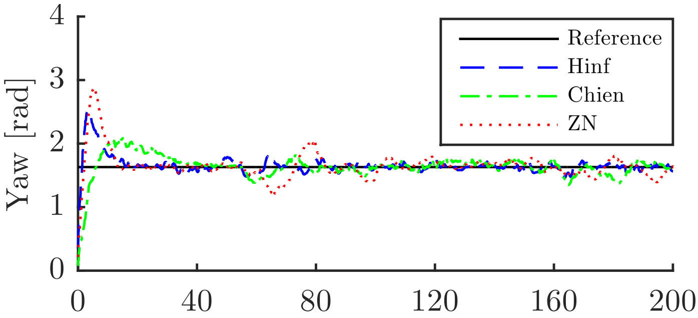
Another two classical controllers are compared over simulations and real experiments to the one proposed here.

- *ZN* controller : $k_{ZN} = (1.32, 0.22, 1.89, 0.5)$.
- *Chien* controller: $k_{Chien} = (1.82, 0.12, 6.4, 0.35)$.



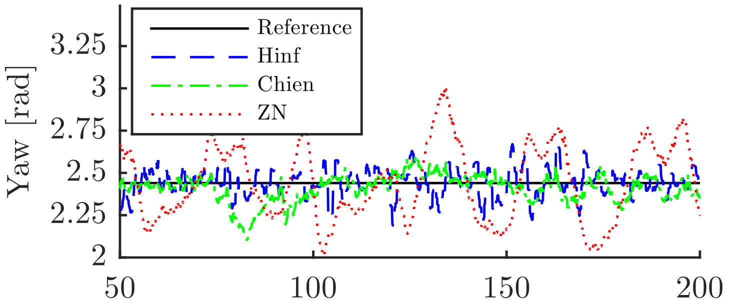


Experimental results - Perturbation in sway direction



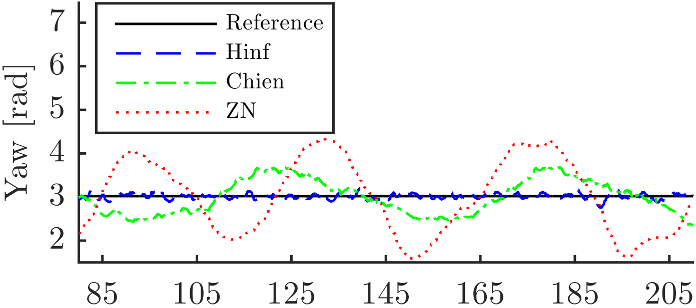
Experiment	RMSE	NMAE	BIAS
ZN	0.2166	0.0689	-0.0204
Hinf	**0.1355**	**0.0386**	**-0.0230**
Chien	0.1738	0.0762	-0.0137

Experimental results - Perturbation at 45 degrees of surge direction



Experiment	RMSE	NMAE	Bias
ZN	0.1742	0.0502	0.0137
Hinf	**0.0650**	**0.0174**	**0.0037**
Chien	0.0755	0.0179	0.0172

Experimental results - Perturbation in surge direction



Experiment	RMSE	NMAE	Bias
ZN	0.3957	0.0749	-0.0037
Hinf	**0.0371**	**0.0059**	**-7.1612e-04**
Chien	0.2548	0.0482	0.0256

Plan

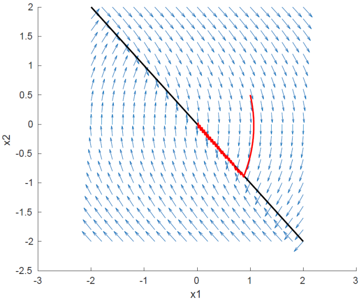
Dynamic constraints.

Idea:

- To use global optimization and interval arithmetic to synthesize SM robust controllers for nonlinear systems.
- To have a measure of this robustness.

Looking back on sufficient conditions for SM establishment:

$$\begin{cases} \dot{\sigma}(\mathbf{x}) < \mathbf{0} & if \quad \sigma(\mathbf{x}) > \mathbf{0} \\ \dot{\sigma}(\mathbf{x}) > \mathbf{0} & if \quad \sigma(\mathbf{x}) < \mathbf{0} \end{cases}$$



Sliding mode problems.

Equivalent control over the sliding surface $\sigma = 0$:

$$u_{eq}(x) = -\frac{L_f\sigma}{L_g\sigma}$$

The sliding condition holds if:

$$u^- \leq u_{eq}(x) \leq u^+$$

Analysis problem

Do the sliding sufficient conditions hold over $\mathbb{X} \subseteq \mathbb{R}^{n_x}$?

Synthesis problem

Given u^+ and u^-, what is the fastest dynamic that can be achieved?

Both imply to compute the minimum and the maximum of u_{eq} over $\mathbb{X}$. $\rightarrow$ But u_{eq} is non-convex in the general case.
$\rightarrow$ Global optimization tools are needed.

Global optimization problem formulation.

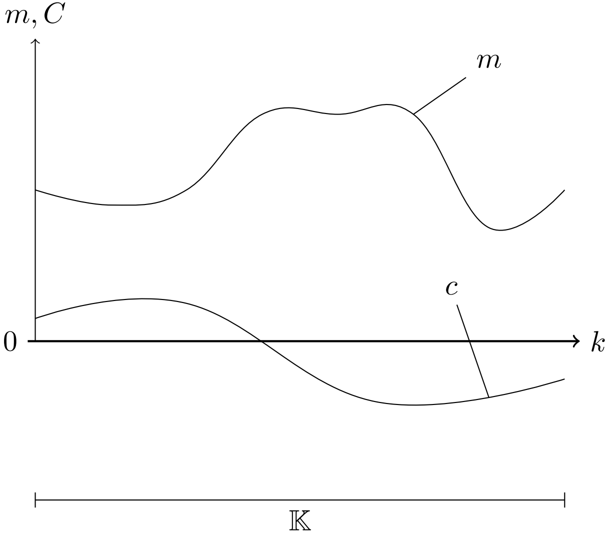
It is possible to formulate:

$$\begin{cases} \inf\limits_{\mathbf{k}\in\mathbb{R}^n} & m(\mathbf{k}) \\ \text{subject to} & c(\mathbf{k}) \leq 0, \end{cases} \tag{12}$$

here:

- m $(\mathbb{R}^n \to \mathbb{R})$ is the objective function.
- $\mathbf{k} \in \mathbb{R}^n$ is the optimization variable.
- c $(\mathbb{R}^n \to \mathbb{R})$ is a function which defines a subset where the solution is searched.

GO, IBBA and set inversion via interval analysis (SIVIA).



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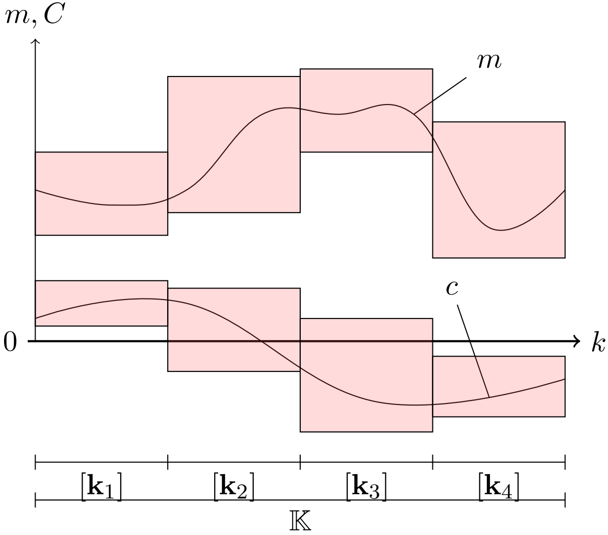

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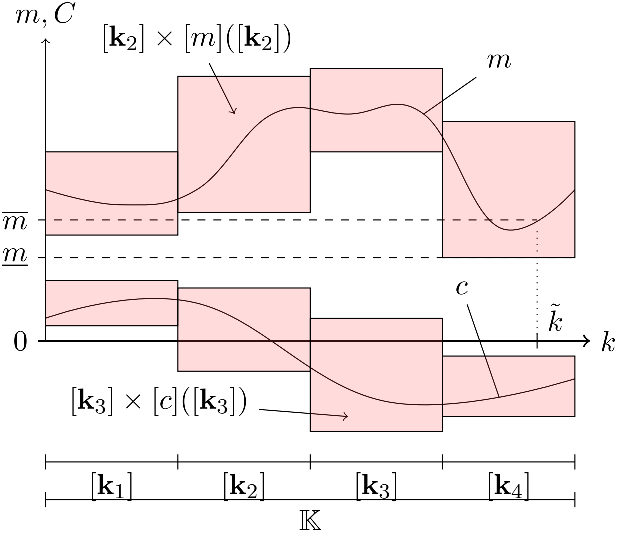

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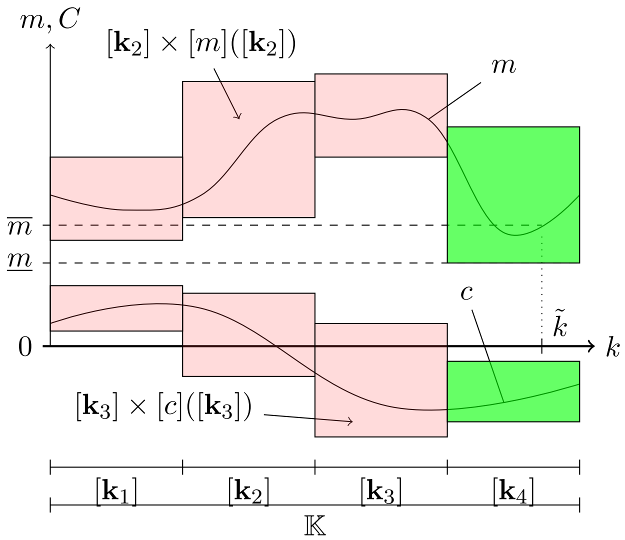

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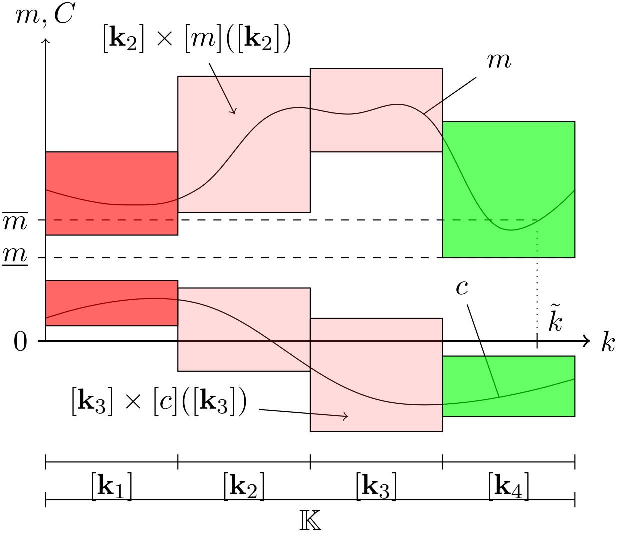

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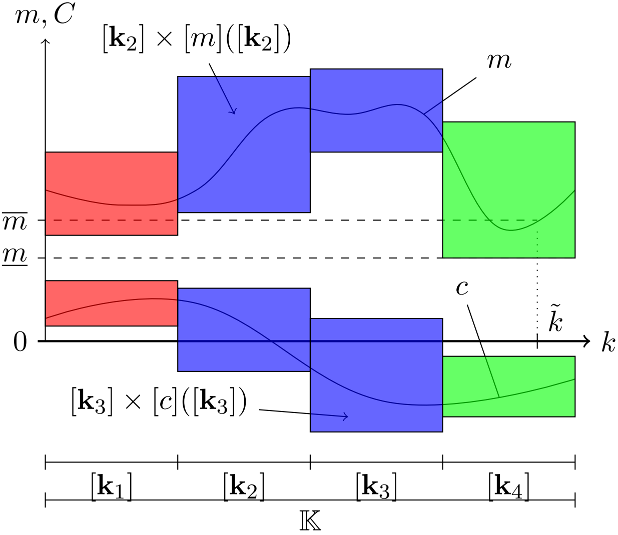

Case study: AUV Ciscrea heave control.

Formulating a SM control with a desired dynamics of the form:

$$\sigma = \dot{e} + \lambda e = 0 \tag{13}$$

with:

- $e = z_d - z$ the tracking error.
- z_d the reference position.
- λ an approaching rate tuning parameter.

Implemented with the discontinuous control action:

$$\tau_{pro} = |\tau_{max}| sign(\sigma) \quad \text{with :} \quad |u^-| = |u^+| = \tau_{max} = 6 \text{ Nm} \tag{14}$$

The equivalent control signal is:

$$u_{eq} = -\lambda \dot{z}(M_{RB} + M_A) + D_L \dot{z} + D_{NL}|\dot{z}|\dot{z} + g(z) - \tau_{env} \tag{15}$$

Synthesis problem.

Synthesis problem

Given u^+ and u^-, what is the fastest dynamic that can be achieved?

Synthesis problem.

Synthesis problem

Given u^+ and u^-, what is the fastest dynamic that can be achieved?

Program to solve:

$$\begin{cases} \sup_{\lambda \in \Delta} \lambda & \\ \text{s. t.} & u^- \leq u_{eq}(\lambda, x), \forall x \in \mathbb{X} \\ & u_{eq}(\lambda, x) \leq u^+, \forall x \in \mathbb{X} \end{cases}$$

$\rightarrow$ Semi infinite program (SIP).

Or equivalently

$$\begin{cases} \sup_{\lambda \in \Delta} \lambda & \\ \text{s. t.} & u^- \leq \min_{x \in \mathbb{X}} u_{eq}(\lambda, x), \\ & \sup_{x \in \mathbb{X}} u_{eq}(\lambda, x) \leq u^+. \end{cases}$$

Synthesis problem.

Synthesis problem

Given u^+ and u^-, what is the fastest dynamic that can be achieved?

$$\begin{cases} \sup_{\lambda \in \Delta} \lambda \\ \text{s. t.} \quad u^- \leq u_{eq}(\lambda, \dot{z}, \tau_{env}), \forall \dot{z} \in [\dot{z}], \forall \tau_{env} \in [\tau_{env}] \\ \quad\quad u_{eq}(\lambda, \dot{z}, \tau_{env}) \leq u^+, \forall \dot{z} \in [\dot{z}], \forall \tau_{env} \in [\tau_{env}] \end{cases}$$

With:

- $[\dot{z}] = [-0.15, 0.15]$
- $[\tau_{env}] = [-3, 3]$

Global maximum over $\Delta = [0, 2]$:

Synthesis problem.

Synthesis problem

Given u^+ and u^-, what is the fastest dynamic that can be achieved?

$$\begin{cases} \sup_{\lambda \in \Delta} \lambda \\ \text{s. t.} \quad u^- \leq u_{eq}(\lambda, \dot{z}, \tau_{env}), \forall \dot{z} \in [\dot{z}], \forall \tau_{env} \in [\tau_{env}] \\ \qquad\quad u_{eq}(\lambda, \dot{z}, \tau_{env}) \leq u^+, \forall \dot{z} \in [\dot{z}], \forall \tau_{env} \in [\tau_{env}] \end{cases}$$

With:

- $[\dot{z}] = [-0.15, 0.15]$
- $[\tau_{env}] = [-3, 3]$

Global maximum over $\Delta = [0, 2]$:

$$\lambda \in [0.3842, 0.3885]$$

Analysis problem I.

Analysis problem

Given u^+,u^- and $\lambda \in \Delta$, what are the speeds at which SM can be achieved?

Analysis problem I.

Analysis problem

Given u^+,u^- and $\lambda \in \Delta$, what are the speeds at which SM can be achieved?

Characterize the feasible set of CSP

$$\begin{cases} u^- \leq u_{eq}(\lambda, \dot{z}, \tau_{env}), \forall \tau_{env} \in [\tau_{env}] \\ u_{eq}(\lambda, \dot{z}, \tau_{env}) \leq u^+, \forall \tau_{env} \in [\tau_{env}] \end{cases}$$

With:

- $|u^-| = |u^+| = \tau_{max} = 6$ Nm
- $[\tau_{env}] = [-3, 3]$

Search domain:

- $\Delta = [0, 2]$
- $[\dot{z}] = [-1, 1]$

Analysis problem I.

Analysis problem

Given u^+,u^- and $\lambda \in \Delta$, what are the speeds at which SM can be achieved?

Characterize the feasible set of CSP

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With:

- $|u^-| = |u^+| = \tau_{max} = 6$ Nm
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Search domain:

- $\Delta = [0, 2]$
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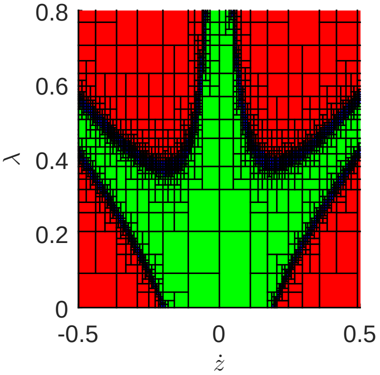
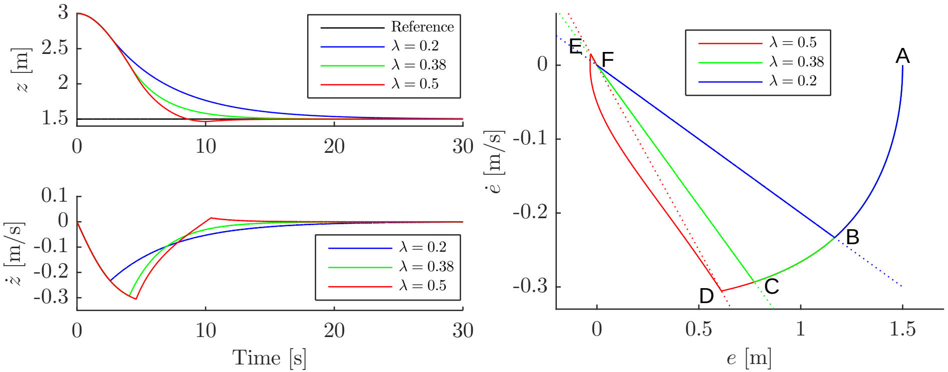


Analysis problem I - System step response.

Analysis problem

Given u^+,u^- and $\lambda \in \Delta$, what are the speeds at which SM can be achieved?



Analysis problem II.

Analysis problem

What happens if we do not know exactly a parameter of the system?

Characterize the feasible set of CSP

$$\begin{cases} u^- \leq u_{eq}(\lambda, \dot{z}, \tau_{env}, M_A), & \forall \tau_{env} \in [\tau_{env}], \forall M_A \in [M_A] \\ u_{eq}(\lambda, \dot{z}, \tau_{env}, M_A) \leq u^+, & \forall \tau_{env} \in [\tau_{env}], \forall M_A \in [M_A] \end{cases}$$

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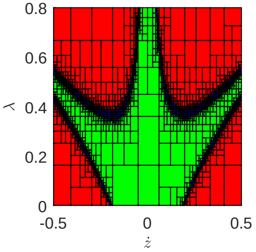
5% M_A variation.



Analysis problem II.

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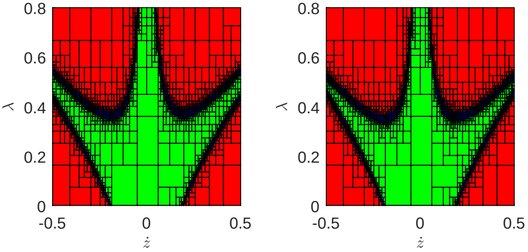
5% M_A variation. 10% M_A variation.



Analysis problem II.

Analysis problem

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Characterize the feasible set of CSP

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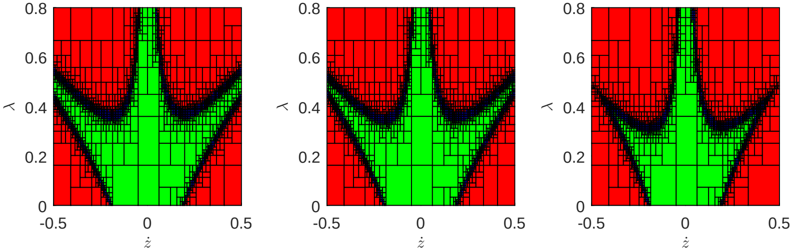
5% M_A variation. 10% M_A variation. 25% M_A variation.



Analysis problem III.

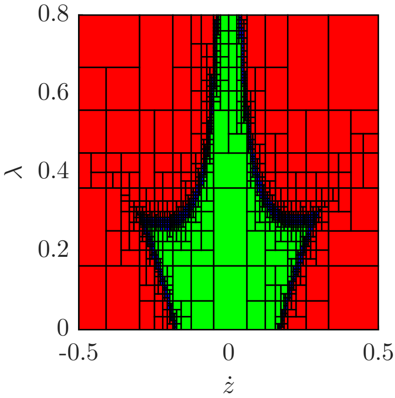
Analysis problem

What happens if we do not know exactly several parameters of the system? (25% variation on M_A and D_{NL} nominal values)

Analysis problem III.

Analysis problem

What happens if we do not know exactly several parameters of the system? (25% variation on M_A and D_{NL} nominal values)



Analysis problem IV.

Analysis problem

Given $\tau_{max} \in [\tau_{max}]$ and $\lambda \in \Delta$, what is the minimal control action we need for a desired λ value?

Analysis problem IV.

Analysis problem

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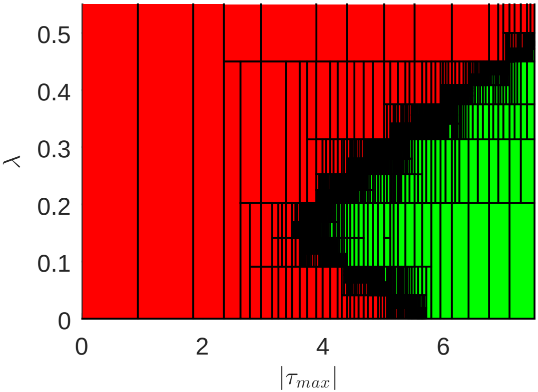

Plan

Particular conclusions - results

- Development of mitigation techniques for input/output constraints, adaptable to already implemented systems.
- Development of a robust tuning technique for PID structure controllers.
- Combination of interval techniques and global optimization for the analysis of robustness of non-linear systems and, in particular for the tuning of SM designs.
  $\rightarrow$ Formalization of the design problem of SM controllers as an SIP.

Publications

- J.L. Rosendo, B. Clement, F. Garelli. Experimental validation of constraint mitigation algorithm in underwater robot depth control. Part I: Journal of Systems and Control Engineering. 2018 (DOI: 10.1177/0959651818791399).
- J.L. Rosendo, D. Monnet, B. Clement, F. Garelli, J. Ninin. Control of an Autonomous Underwater Vehicle subject to robustness constraints. 9th IFAC Symposium on Robust Control Design (ROCOND'18). Florianopolis, Brazil. IFAC-PapersOnLine: Volume 51, Issue 25, 2018, Pages 322-327.
- D. Monnet, J.L. Rosendo, H. De Battista, B. Clement, J. Ninin, F. Garelli. A global optimization approach for non-linear sliding mode control analysis and design. 9th IFAC Symposium on Robust Control Design (ROCOND'18). Florianopolis, Brazil. IFAC-PapersOnLine: Volume 51, Issue 25, 2018, Pages 128-133.
- J.L. Rosendo, D. Monnet, H. De Battista, J. Ninin, B. Clement, F. Garelli. Sliding mode control analysis and design for an AUV application using global optimization techniques. Nonlinear Dynamics (submitted).
- J.L. Rosendo, F. Garelli, H. De Battista. Obstacle avoidance with path restrictions in autonomous underwater vehicles. AADECA 2018 - Semana del Control Automático - 26º Congreso Argentino de Control Automático. Buenos Aires, Argentina.
- J.L. Rosendo, F. Garelli, H. De Battista, F. Valenciaga. Obstacle avoidance under strict path following. XVII Workshop on Information Processing and Control (RPIC). Argentina, Mar del Plata. 2017. DOI: 10.23919/RPIC.2017.8214344.
- J.L. Rosendo, B. Clement, F. Garelli. Acondicionamiento de la referencia utilizando modos deslizantes en aplicaciones de seguimiento de camino en AUV. Cuartas Jornadas de Investigación, Transferencia y Extensión de la Facultad de Ingeniería. UNLP. Facultad de Ingeniería, Universidad Nacional de La Plata. Argentina. La Plata.
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- J.L. Rosendo, D. Monnet, B. Clement, F. Garelli. Control of an Autonomous Underwater Vehicule under robustness constraints. Workshop. SWIM 2016 (Summer Workshop on Interval Methods). École Normale Supérieure de Lyon (ENS de Lyon). Francia. Lyon.
- J.L. Rosendo, F. Garelli, B. Clement, H. De Battista. Mitigation of the saturation effect in AUV path following applications. AADECA 2016. Argentina. Buenos Aires. 2016. ISBN 978-950-99994-9-7.

Global conclusions - Acknowledgments

- An incursion in the robotics world was made from the point of view of control theory.
- Theoretical and practical knowledge was obtained that will serve as the basis for further projects in the area of robotics at UNLP.
- Collaboration was achieved with another research group, which is expected to continue in time.

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- UNLP - FI - LEICI.
- ENSTA Bretagne.
- Eiffel scholarship.