Guaranteed simulation and synthesis of Cyber-Physical Systems

INRIA Rennes

Audition Concours CRCN

Adrien Le Coënt
https://adrienlecoent.github.io

Aalborg University

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Education

Postdoctoral fellow (Aalborg University, 2017 - Present)
Guaranteed synthesis of hybrid systems using timed automata abstractions

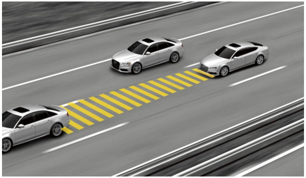
PhD (École Normale Supérieure de Cachan, 2014 - 2017)
Guaranteed control synthesis for switched space-time dynamical systems

Master (École Normale Supérieure de Cachan, 2013 - 2014)
Advanced Techniques in Structural Computations

Agrégation de Sciences Industrielles (2013)

Research internship (Technical University of Denmark, 2012)
Passive shunt damping of vibrating beams using piezoelectric devices

Context: control systems



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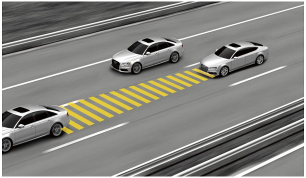

Issues

guaranteed control synthesis for safety/stability/reachability
nonlinear systems, PDEs

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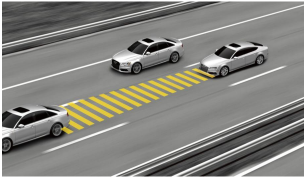

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Applications

safety critical systems
guaranteed performance

Switched Systems

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A continuous-time switched system

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- state $x \in \mathbb{R}^n$
- bounded perturbation $w(\cdot) : \mathbb{R}^+ \longrightarrow D \subset \mathbb{R}^m$
- switching signal $\sigma(\cdot) : \mathbb{R}^+ \longrightarrow U$ with $U = \{1, \dots, N\}$ (piecewise constant)

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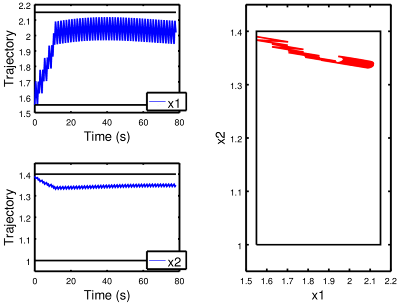
DC-DC converter:
stabilize voltage and current

$$x = \begin{pmatrix} V \\ I \end{pmatrix}$$



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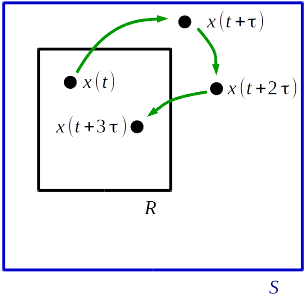
Given two sets R, S:

- (R, S)-stability: $x(t)$ returns in R infinitely often, at some multiples of sampling period τ, and always stays in S



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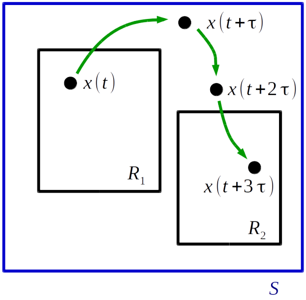
At each sampling time $k\tau$, find the appropriate switched mode $u \in U$ according to the current value of x, in order to achieve some objectives:

Given three sets R_1, R_2, S:

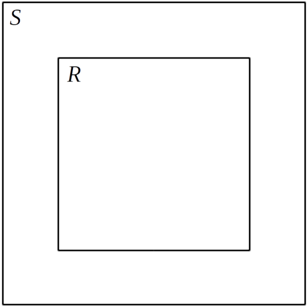
- (R_1, R_2, S)-reachability: $x(t)$ starting in R_1 reaches R_2 after some multiples of sampling period τ, and always stays in S



Control tiling procedure

$$\dot{x}(t) = f_{\sigma(t)}(x(t), d(t))$$

Goal: from any $x \in R$, return in R while always staying in S.



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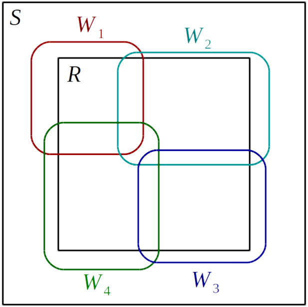

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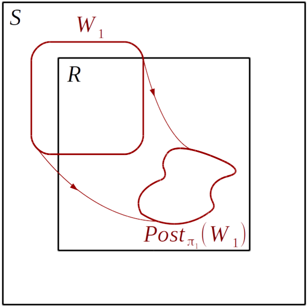

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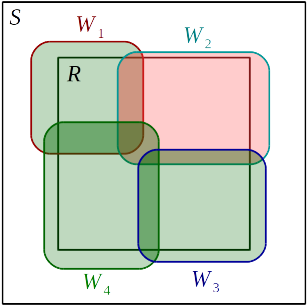

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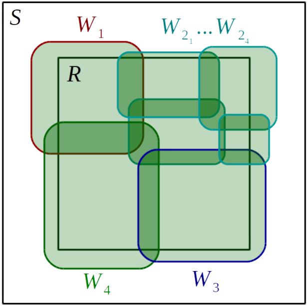

Basic idea:

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- Look for input sequences mapping (set propagation) the tiles into R while always staying in S
- If it fails, generate another covering.

Limits

- Requires the computation of the reachable set
  - unknown in general for nonlinear systems
  - can be approximated using numerical schemes and/or strong hypotheses (restricted class)

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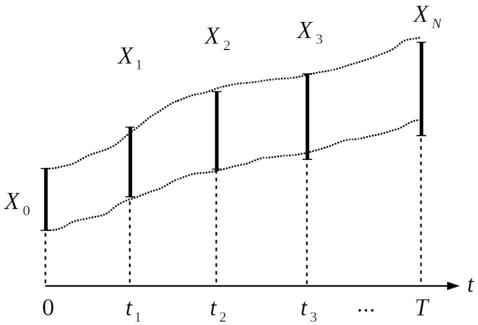
Contributions

- Guaranteed reachable set computation for a large class of nonlinear systems with guaranteed numerical schemes
- Handling higher dimensions using compositionality
- Synthesizing controllers for PDEs using Model Order Reduction

Validated simulation

Runge-Kutta numerical scheme:

- Computation of a sequence of approximations (t_n, X_n) of the solution $X(t; X_0)$
- X_i computed with the previous step: $X_i = h(t_{i-1}, X_{i-1})$



[Le Coënt, Sandretto, Chapoutot, Fribourg, FMSD journal, 2018]
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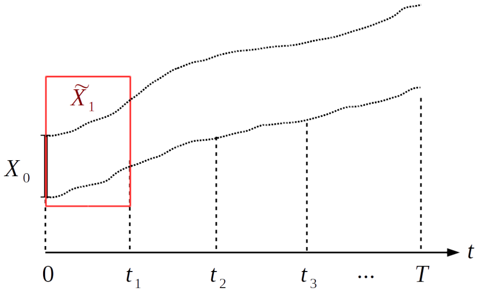

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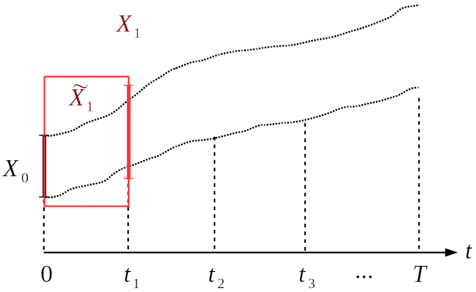

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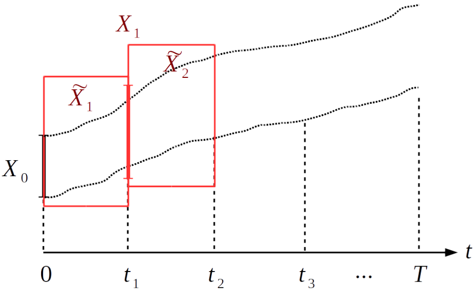

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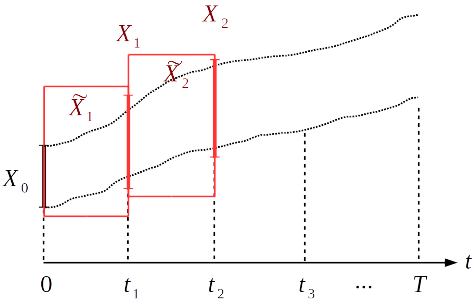

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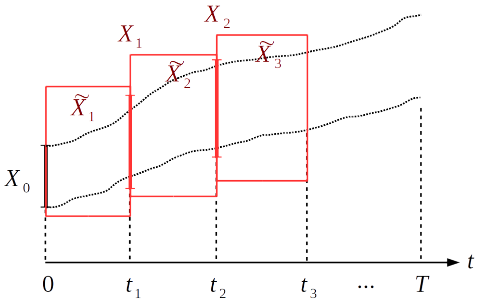

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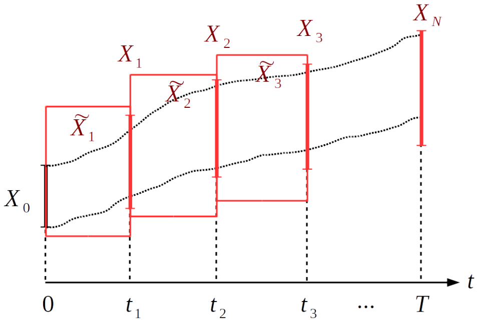

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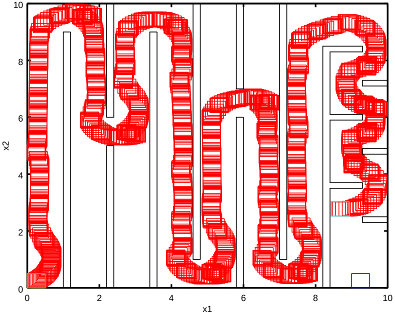
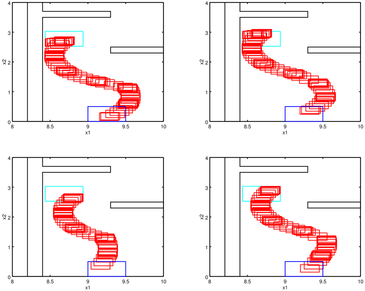
Illustration: a path planning problem



$$\begin{aligned}\dot{x} &= v_0 \frac{\cos(\alpha+\theta)}{\cos(\alpha)}\\ \dot{y} &= v_0 \frac{\sin(\alpha+\theta)}{\cos(\alpha)}\\ \dot{\theta} &= \frac{v_0}{b}\tan(\delta)\end{aligned}$$



Renewing the Euler scheme with the OSL property

$(H1)$ (One-sided Lipschitz): for all $j \in U$, there exists a constant $\lambda_j \in \mathbb{R}$ such that

$$\langle f_j(y) - f_j(x), y - x \rangle \leq \lambda_j \|y - x\|^2 \quad \forall x, y \in S,$$

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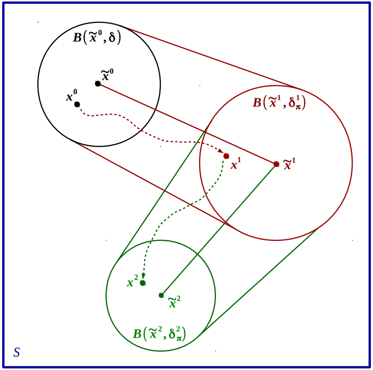

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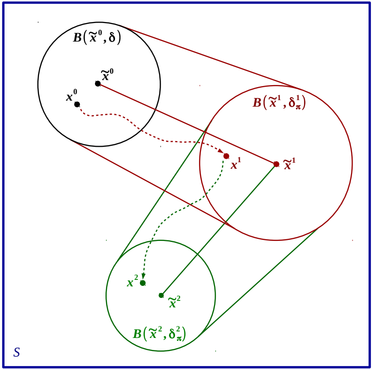
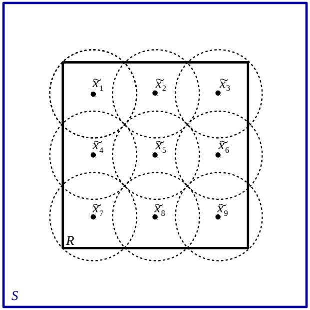
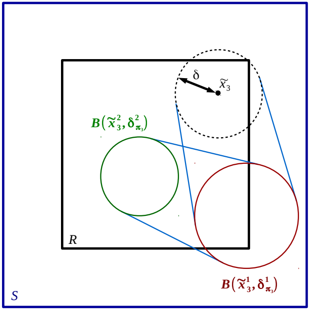


- Extremely fast computations
- Applicable to a large class of systems
- Arbitrary sampling time
- Simple implementation

[Le Coënt, De Vuyst, Chamoin, Fribourg, SNR'17]

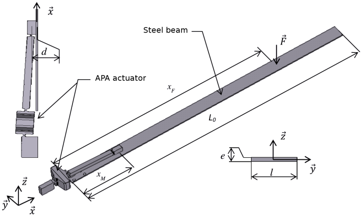
Control synthesis





[Le Coënt, De Vuyst, Chamoin, Fribourg, SNR'17]

Dimensional limits



Distributed control synthesis

Splitting of the system

$$\dot{x}_1 = f_1(x_1, x_2, u_1)$$
$$\dot{x}_2 = f_2(x_1, x_2, u_2)$$

Control objective: (R, S)-stability with $R = R_1 \times R_2$, $S = S_1 \times S_2$

[Le Coënt, Fribourg, Markey, De Vuyst, Chamoin, TCS journal, 2018]
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- Basic idea: (R_1, S_1)-stability synthesis for sub-system 1 by considering sub-system 2 as a bounded perturbation (in S_2) and vice-versa
- Requirements:
  - Separated control (often possible)
  - Handling of bounded perturbations
  - Few interactions between sub-systems
  - Both syntheses successful

[Le Coënt, Fribourg, Markey, De Vuyst, Chamoin, TCS journal, 2018]
[Le Coënt, Fribourg, Markey, De Vuyst, Chamoin, RP'16]
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Principle of the distributed synthesis

A discrete-time distributed control system:

$$x_1(t+1) = f_1(x_1(t), x_2(t), u_1(t))$$
$$x_2(t+1) = f_2(x_1(t), x_2(t), u_2(t))$$

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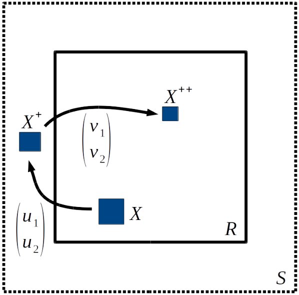

- $X \subset R$
- $X^{+} = f(X, \begin{pmatrix} u_1 \\ u_2 \end{pmatrix}) \subset S$
- $X^{++} = f(X^{+}, \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}) \subset R$
- Pattern $\begin{pmatrix} u_1 \\ u_2 \end{pmatrix}, \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}$ depends on X

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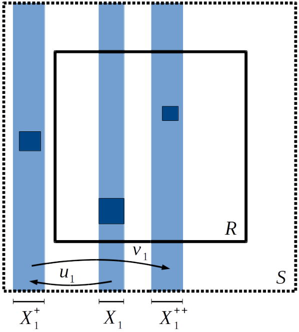

- $X_1 \subset R_1$
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- $X_1^{++} = f_1(X_1^+, S_2, v_1) \subset R_1$

- Pattern u_1, v_1 depends only on X_1

Seluxit case study

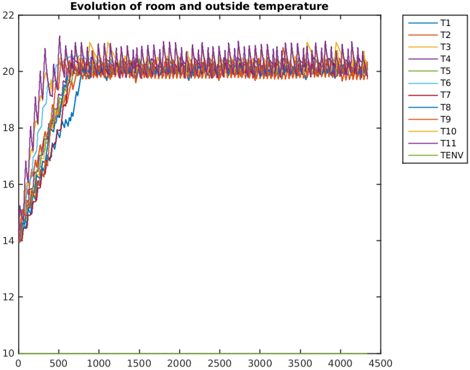
Kim G. Larsen, Marius Mikučionis, Marco Muniz, Jiri Srba, Jakob H. Taankvist. *Online and Compositional Learning of Controllers with Application to Floor Heating*. Tools and Algorithms for Construction and Analysis of Systems 2016.

Seluxit case study, guaranteed reachability and stability

Decomposition in 5 + 6 rooms

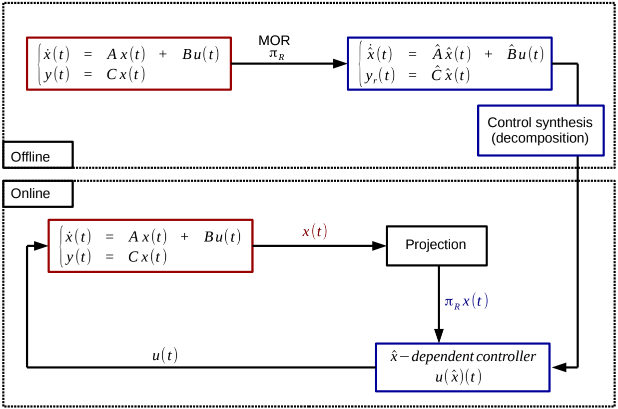
Input:
$R = [18, 22]^{11}$
$S = [17.5, 22.5]^{11}$
$T_{env} = 10$

Results:
Iterated reachability in 15 steps
Synthesis time: 6h



Simulation of the Seluxit case study plotted with time (in min) for $T_{env} = 10^\circ C$.

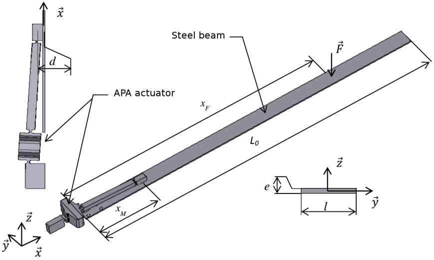
Dealing with high dimensionality : Model Order Reduction

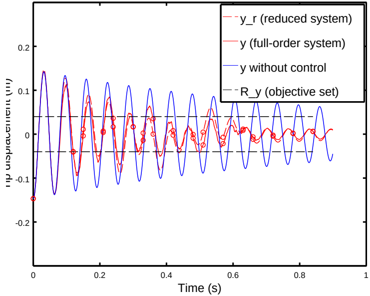


[Le Coënt, De Vuyst, Chamoin, Rey, Fribourg, IJDC journal, 2016]
[Le Coënt, De Vuyst, Chamoin, Rey, Fribourg, SynCoP'15]

Application

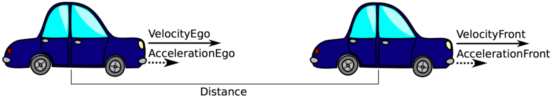
- Vibration (online) control of a cantilever beam: $n = 120$ and $n_r = 4$





[Le Coënt, De Vuyst, Chamoin, Rey, Fribourg, IJDC journal, 2016]
[Le Coënt, De Vuyst, Chamoin, Rey, Fribourg, SynCoP'15]

Timed game abstraction of a cruise control application in UPPAAL TIGA



- Timed game abstraction allowing more complex behaviour
- Integer approximation of the continuous dynamics to keep the problem decidable
- Safety control synthesis using UPPAAL TIGA
- Further optimizations using UPPAAL STRATEGO

[Larsen, Le Coënt, Mikučionis, Taankvist, CyPhy'18]

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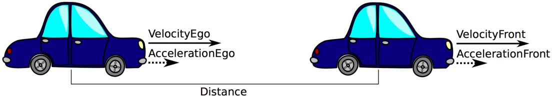

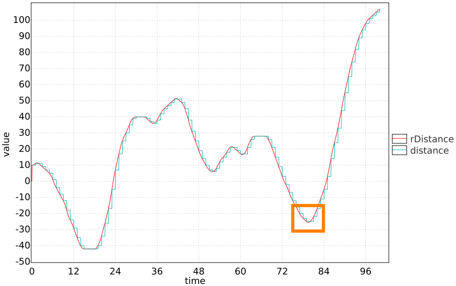

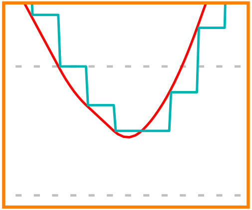

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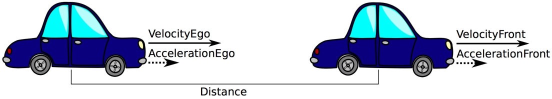
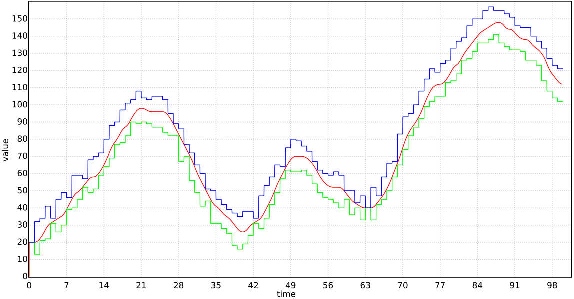


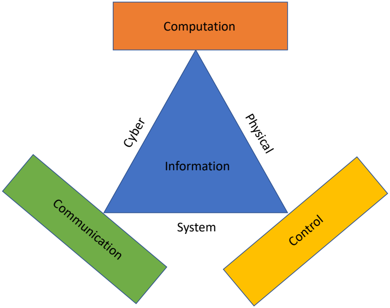


[Larsen, Le Coënt, Mikučionis, Taankvist, CyPhy'18]

Research program : guaranteed simulation and synthesis of Cyber-Physical Systems

Why ?

Safety critical applications: autonomous vehicles, smart grids, medical monitoring, robotics...



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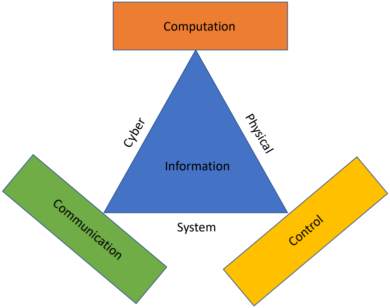
Current barriers : Accuracy, dimensionality, complexity of the systems (DAEs, resets, asynchronous systems) and generality of approaches (specific methods for different PDEs)



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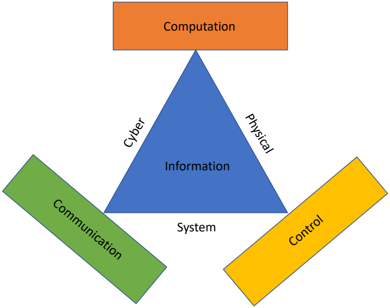
Lines of research :

- Guaranteed simulation
- Compositional synthesis
- General framework for PDEs



Guaranteed simulation

- Guaranteed simulation with numerical schemes
  Extends previous work for ODEs using new numerical schemes
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  $\langle f(y) - f(x), y - x \rangle \leq \lambda \|y - x\|^2 \quad \forall x, y \in S$
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  [Sogokon, Ghorbal et al., A Method for Invariant Generation for Polynomial Continuous Systems, 2016]
- Guaranteed simulation for DAEs and hybrid systems
  Issues: algebraic condition, state guards, topology for sound approximation
  Approach: implicit schemes, incremental difficulty

$$\dot{x} = f(y, x)$$
$$0 = g(y, x)$$

[Caillaud, Ghorbal, Benveniste et al., Structural Analysis of Multi-Mode DAE, 2017]

Compositional synthesis

- Contract-based design for synchronous systems
  Motivated by the 11-room case study
  Unlocks: better performances, application to smart grids
  Approach: energy distribution could be solved with Assume-Guarantee contracts
  [Benveniste, Caillaud et al., Contracts for System Design, 2012]

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- Asynchronous inter-connected systems
  Compositional synthesis works for synchronous switched systems
  But we need asynchronous switchings !
  Unlocks: realistic case studies (*e.g.* cruise-control)
  Approach: guaranteed simulation with arbitrary switching times & timed game abstraction
  [Larsen, Le Coënt et al., Guaranteed control synthesis for continuous systems in Uppaal Tiga, 2018]

Partial Differential Equations

- A general framework for PDEs
  Basic idea :
  PDE + discretization = HD-ODE
  HD-ODE + MOR = ODE
  ODE + tiling based synthesis + error bounding = guaranteed control
  - First: linear 1D
    [Le Coënt, Guaranteed control synthesis for switched space-time dynamical systems, 2017]
  - Then: nonlinear 1D
    [De Vuyst, Toumi, Empirical Interpolation Decomposition, 2018]
  - Last: multi-D

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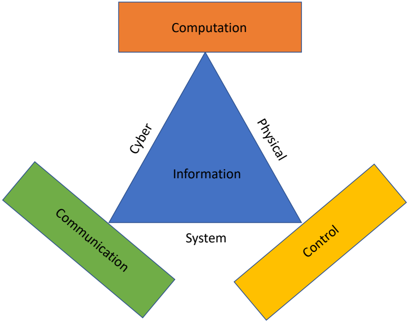
  - Last: multi-D
- Domain decomposition methods and compositional analysis
  Long term dream for overcoming any dimensional barrier

Research program

Équipe-Projet HYCOMES (Benoît Caillaud, Khalil Ghorbal, Albert Benveniste)

- Faithful simulation, modularity, keeping models close to physics
- Contract-based design and interface theories, with applications to requirements engineering



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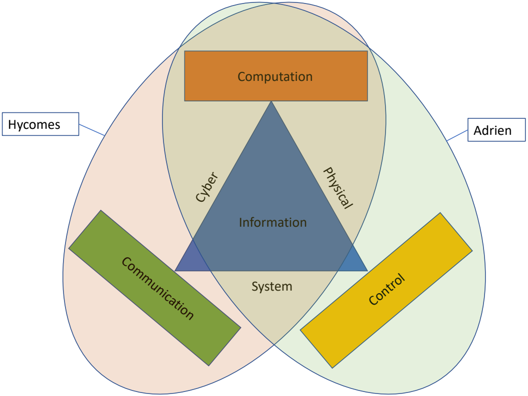

Ecosystem

Guaranteed simulation

Hycomes	U2IS	LAAS
Khalil Ghorbal	Alexandre Chapoutot	Victor Magron
Benoît Caillaud	Julien Alexandre dit Sandretto	

Compositional synthesis

Hycomes	AAU	LSV	L2S
Albert Benveniste	Kim Larsen	Laurent Fribourg	Antoine Girard
Benoît Caillaud			

DAEs

Hycomes
Khalil Ghorbal
Benoît Caillaud

PDEs

UTC	LMT
Florian De Vuyst	Ludovic Chamoin

Industrial collaborations, research supervision, project funding

- Industrial collaborations and case-studies
  - Nilfisk () : lifetime and state-of-charge optimization of lead-acid batteries
  - Seluxit () : 11 room floor heating case-study
- Research supervision
  - Research internship :
    - A numerical-symbolic hybrid method for approx. solutions of parameter-dependent PDEs[1]
    - Analysis and practice of the PARAEXP algorithm[2]
  - Bachelor's project : Prediction Methods for Finite Control Set - Model Predictive Control[3]
- Projects supporting this research
  ERC Lasso, Innovation Fund Denmark DiCyPS, Institut Farman SWITCHDESIGN2 and RAILBOOL, ANR iCODE, ANR Digicosme, ERC Cassting

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[1] A. Guérin, J. Delhom

[2] R. Alison, G. Brunet, P. Jusselin, F. Koechlin

[3] A. G. Weirsøe, C. S. Mathisen, J. L. Haslund, M. Nielsen

Summary

Project : Guaranteed simulation and synthesis of Cyber-Physical Systems

Experience

(2017 - 2019) Post doc (Aalborg, 🇩🇰)
(2014 - 2017) PhD (Cachan, 🇫🇷)
(2012) Research internship (Copenhagen, 🇩🇰)

13 publications (4 journals, 9 conferences) + 3 submissions

Guaranteed simulation: FMSD, SNR'16, SNR'17, ADHS'18, CyPhy'18, CDC'19 (subm.), NAHS (subm.)
Compositional synthesis: TCS, RP'17, RP'16, RP'16
Control of PDEs: IJDC, JMES, SynCoP'15
Timed game abstractions: CyPhy'18, QEST'19 (subm.)

Case of undiscretized PDE problems

Difficulty:

- The problem becomes infinite-dimensional;
- Even spatially discretized, the *curse of dimensionality* makes the former approaches (bisection, ball overlapping, ...) irrelevant.

$\Longrightarrow$ requires model order reduction (MOR)