## CONTROL OF STATE-CONSTRAINED DYNAMICAL SYSTEMS

## 24 - 27 SEPTEMBER 2019, UNIVERSIDAD TÉCNICA FEDERICO SANTA MARÍA, VALPARAÍSO, CHILE

## AIMS AND SCOPES

The aim of this event is twofold. First, it is to bring together researchers working on optimal control of state-constrained dynamical systems, with an emphasis on sweeping processes and related fields, trying to foster new scientific relations. Secondly, it is to promote this field of optimization among graduate and undergraduate students. For these reasons this event will include two mini-courses on sweeping processes and optimality conditions.

The scope of the conference is mainly concerned with (but not limited to):

- the dynamics and the control of Moreau's sweeping process or of rate independent processes;
- the control of (classical) deterministic control problems with state constraints;
- models from science and technology involving general state constraints.

## Scientific and organizing committe

- Giovanni Colombo, Università di Padova, Padova, Italy
- Cristopher Hermosilla, UTFSM, Valparaíso, Chile
- Emilio Vilches, Universidad de O'Higgins, Rancagua, Chile



UTFSM, Valparaíso, Chile.

This activity is organized by UTFSM and Universidad de O'Higgins with the support of REDES Project REDI 170200 from Conicyt, Center for Mathematical Modeling (CMM) and Universidad de O'Higgins.

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## MINICOURSES

•	Giovanni Colombo, Università di Padova, Italy.	6
	Title: An Introduction to Moreau's Sweeping Process and Some Results on Its Control.	
	Lectures: Tuesday and Thursday 11:00 - 12:30; Wednesday and Friday 09:00 - 10:30.	
•	Boris Mordukhovich, Wayne State University, USA.	7

Title: Optimal Control of Sweeping Processes with Applications. Lectures: Tuesday and Thursday 09:00 - 10:30; Wednesday and Friday 11:00 - 12:30.

# PLENARY TALKS

• Bernard Brogliato, INRIA Grenoble Rhône-Alpes, France. Talk: State Observers Design and Analysis for Set-Valued Lur'e Systems. Thursday 14:15-15:15	8
• Pavel Krejči, Czech Academy of Sciences, Czech Republic. Talk: Control and controllability of PDEs with hysteresis. Tuesday 14:15-15:15	9
• Michele Palladino, Gran Sasso Science Institute, Italy. Talk: Sweeping Process and Optimal Control. Wednesday 14:15-15:15	10
• Vincenzo Recupero, Politecnico di Torino, Italy. Talk: The Role of Geodesics for the Excess in the Moreau's Sweeping Processes Friday 14:15-15:15	. 11

# INVITED TALKS

•	María Soledad Aronna, Fundação Getulio Vargas, Brazil. Talk: About Second Order Conditions in the Presence of State Constraints. Wednesday 15:30 - 16:00	12
•	Jaime Becerril, Universidade do Porto, Portugal. Talk: A Weak Maximum Principle for Problems with Nonregular Mixed Constraints. Thursday 17:00 - 17:30	13
•	Tan Cao, State University of New York, Korea. Talk: Discrete Approximations of a Controlled Sweeping Process over Polyhedral Sets w Perturbations. Wednesday 17:00 - 17:30	14 vith
•	Aris Daniilidis, Universidad de Chile, Chile. Talk: From the Gradient Dynamics to the Sweeping Process. Tuesday 15:30 - 16:00	15
•	Paolo Gidoni, Czech Academy of Sciences, Czech Republic. Talk: On the Optimal Control for the Locomotion of Rate-Independent Soft Crawlers. Tuesday 16:00 - 16:30	16

<ul> <li>Nathalie Khalil, Universidade do Porto, Portugal. Talk: Problems with Violated Classical Inward Pointing Condition. Thursday 16:00 - 16:30</li> </ul>	17
• Fernando Lobo Pereira, Universidade do Porto, Portugal Talk: On the Optimal Control of Bilevel Sweeping Processes. Tuesday 17:30 - 18:00	18
• Oleg Makarenkov, University of Texas at Dallas, USA. Talk: Global Asymptotic Stability of Perturbed Sweeping Processes. Friday 15:30 - 16:00	19
<ul> <li>Dinh Hoang Nguyen, Universidad de Concepción, Chile. Talk: Optimal Control of Sweeping Processes: Construction of Discrete Approx via Γ-convergence. Wednesday 17:30 - 18:00</li> </ul>	20 cimations
<ul> <li>Athena Picarelli, Universitá di Verona, Italy Talk: Optimal Management of Pumped Hydroelectric Production with State Con Optimal Control. Thursday 17:30 - 18:00</li> </ul>	21 nstrained
• Geraldo Nunes Silva, Universidade Estadual Paulista, Brazil. Talk: Constrained Minimax Control Problems. Wednesday 16:00 - 16:30	22
• Emilio Vilches, Universidad de O'Higgins, Chile. Talk: On the Lyapunov Stability of Sweeping Process. Friday 16:00 - 16:30	23
• Peter Wolenski, Louisiana State University, USA. Talk: Fully Convex Bolza Problems with State Constraints and Impulses. Tuesday 17:00 - 17:30	24
• Hasnaa Zidani, ENSTA ParisTech, France. Talk: Sensitivity Relations for Some Control Problems with State Constraints. Thursday 15:30 - 16:00	25

	Tuesday	Wednesday	Thursday	Friday
000 1030	B. Mordukhovich	G. Colombo	B. Mordukhovich	G. Colombo
9 -10	(Lecture 1)	(Lecture 2)	(Lecture 3)	(Lecture 4)
$10^{30}$ -11 <sup>00</sup>	Coffee Break			
1100 1030	G. Colombo	B. Mordukhovich	G. Colombo	B. Mordukhovich
11 -12	(Lecture 1)	(Lecture 2)	(Lecture 3)	(Lecture 4)
$12^{30}$ - $14^{15}$	Lunch			
$14^{15}$ - $15^{15}$	P. Krejči	M. Palladino	B. Brogliato	V. Recupero
$15^{15}$ - $15^{30}$	Break			
$15^{30}$ - $16^{00}$	A. Daniilidis	M.S. Aronna	H. Zidani	O. Makarenkov
$16^{00}$ - $16^{30}$	P. Gidoni	G.N. Silva	N. Khalil	E. Vilches
$16^{30}$ -17 <sup>00</sup>	Coffee Break			Closing
$17^{00}$ - $17^{30}$	P. Wolenksi	T. Cao	J. Becerril	Cocktail
$17^{30}$ -18 <sup>00</sup>	F. Lobo Pereira	N.D. Hoang	A. Picarelli	
$2000_{2300}$			Social Dinner	
20 -23			(Restaurant Ilo Mapu)	

## Program

# SOCIAL DINNER

A Social Dinner will take place on **September 26, 2019** at 20:00 in **Ilo Mapu** Restaurant (6 Norte 228, Viña del Mar, Chile).

## Minicourse

# AN INTRODUCTION TO MOREAU'S SWEEPING PROCESS AND SOME RESULTS ON ITS CONTROL

#### GIOVANNI COLOMBO

The plan for these lectures is the following:

- (1) Some preliminaries, prox-regular sets and metric projection (with full proofs). Some models involving the sweeping process and some explanations on its kinematics.
- (2) In Hilbert spaces: the catching up algorithm and its convergence in the prox-regular case (with full proofs).
- (3) In Hilbert spaces: the perturbed sweeping process, with a particular emphasis on the time independent case. Existence and uniqueness via regularization (with full proofs, but possibly only in the time independent and convex case). An overview of the literature on existence and uniqueness (without proofs).
- (4) In  $\mathbb{R}^n$ : some results on necessary optimality conditions via the regularization method and/or Hamilton-Jacobi theory for the minimum time function.

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#### Mini-course

# OPTIMAL CONTROL OF SWEEPING PROCESSES WITH APPLICATIONS

#### BORIS MORDUKHOVICH

These lectures are devoted to new classes of optimal control problems governed by sweeping/Moreau processes that are described by discontinuous differential inclusions. We consider several types of such control systems all of which contain pointwise constraints a state and control functions. The approach we develop combines the refined method of discrete approximations with advanced tools of variational analysis and generalized differentiation. In this way, we establish well-posedness and appropriate convergence of discrete approximations and derive necessary optimality conditions for the controlled sweeping processes. Some examples and applications to practical models will be also presented in the lectures.

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#### **Plenary** talk

# STATE OBSERVERS DESIGN AND ANALYSIS FOR SET-VALUED LUR'E SYSTEMS

#### BERNARD BROGLIATO

This talk will focus on the problem of designing asymptotically stable state observers for a class of differential inclusions, made of a linear time-invariant system in negative feedback with a set-valued (possibly time-varying and non-monotone) static nonlinearity. These setvalued dynamical systems are an extension of the classical Lur'e systems, widely studied in Automatic Control since their introduction by Lur'e in 1945. Dissipativity, maximal monotonicity, prox-regularity are crucial properties for the well-posedness and the stability analysis. Systems with absolutely continuous solutions, and with solutions of local bounded variation (hence possible state jumps), will be considered.

INRIA GRENOBLE RHÔNE-ALPES, FRANCE, EMAIL: bernard.brogliato@inria.fr

#### Plenary talk

## CONTROL AND CONTROLLABILITY OF PDES WITH HYSTERESIS

## PAVEL KREJČI

For a diffusion equation with a complex hysteresis operator we consider the problem of controllability, that is, finding a control which guarantees that the solution reaches a desired value at a given time. It is solved here by a constructive method based on a two-parameter penalty argument. One small parameter penalizes the distance of the solution at final time from the expected value, the second one represents viscous regularization of the underlying rate independent variational inequalities in the hysteresis term. We prove that a solution to the controllability problem can be obtained by passing to the singular limit in the doubly degenerate control system.

This is a joint work with Chiara Gavioli from Modena.

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**Plenary** talk

## SWEEPING PROCESS AND OPTIMAL CONTROL

## MICHELE PALLADINO

In this talk, we address some recent advances in Dynamic Optimization for the Controlled Sweeping Process (also known in the literature as Moreaus process)

$$(*)$$
  $\dot{x} \in -N_{C(t)}(x) + f(t, x, u), \quad u \in U,$ 

where  $C(\cdot)$  is a Lipschitz continuous set-valued mapping. Such a framework is a general way to model optimal control problems with state constraints depending on time, but it also arises in many other applications like crowd motion, electric circuit, mechanical system modeling and soft-robotic. In the first part of the talk we present a minimum time problem related to (\*) and we characterize the minimum time function T(t, x) as the continuous solution of a set of Hamilton-Jacobi inequalities; in the second part we discuss some recent advances for what concerns the necessary conditions for a general Mayer problem. In both cases, the main difficulty is due to the presence of the normal cone  $N_{C(t)}(x)$  on the right hand side of (\*), which is a not Lipschitz continuous mapping with respect to x and contains implicitly the state constraint  $x(t) \in C(t)$ .

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## **Plenary** talk

# THE ROLE OF GEODESICS FOR THE EXCESS IN THE MOREAU'S SWEEPING PROCESSES

## VINCENZO RECUPERO

We present some new classes of set-valued geodesics for the asymmetric distance called "excess" and we show how these geodesics can be exploited in the analysis of the Moreau's sweeping processes with local bounded retraction.

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## Invited talk

# ABOUT SECOND ORDER CONDITIONS IN THE PRESENCE OF STATE CONSTRAINTS

#### MARIA SOLEDAD ARONNA

For optimal control problems of ordinary differential equations that are affine with respect to the control and subject to state and control constraints, we present second order necessary and sufficient optimality conditions. If the time allows it, we will comment on associated numerical schemes and its convergence.

FUNDAÇÃO GETULIO VARGAS, BRAZIL, EMAIL: soledad.aronna@fgv.br

Invited talk

# A WEAK MAXIMUM PRINCIPLE FOR PROBLEMS WITH NONREGULAR MIXED CONSTRAINTS.

#### JORGE BECERRIL

First-order necessary conditions for optimal control problems with mixed constraints are well-known when some regularity criterion is satisfied. In contrast, problems involving nonregular mixed constraints have received little attention despite the fact that they are becoming increasingly relevant in many areas such as robotics and problems involving sweeping systems. We present necessary conditions applicable to problems comprising nonregular mixed constraints derived via infinite-dimensional optimization techniques. Moreover, we show how regularity reduces these new conditions to the classical ones and how pure state constrained problems can also be treated as a particular case.

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Invited talk

# DISCRETE APPROXIMATIONS OF A CONTROLLED SWEEPING PROCESS OVER POLYHEDRAL SETS WITH PERTURBATIONS

## TAN H. CAO

The talk involves a class of optimal control problems governed by a perturbed sweeping (Moreau) process with the moving convex polyhedral set, where the controls are used to determine the best shape of the moving set and select the best perturbation in order to optimize the given Bolza-type problem which depends on controls and state variables as well as their velocities. Using the method of discrete approximations, we approximate the optimal control problem under consideration by a sequence of well-posed finite-dimensional problems whose optimal solutions strongly converge to that of the original controlled sweeping problem under less restrictive assumptions on the controls and state variables. This approach together with the advanced tools of variational analysis and generalized differentiation allows us to efficiently derive the necessary optimality conditions for the discretized control problems. The obtained results can be considered as necessary sub-optimality conditions and hence propose a numerical scheme for searching optimal solutions to the original controlled perturbed sweeping process. Finally, passing these conditions to the limit allows us to derive the necessary optimality conditions for the original problem.

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## Invited talk

## FROM THE GRADIENT DYNAMICS TO THE SWEEPING PROCESS

## ARIS DANIILIDIS

In this talk we review the desingularization of the derivative for a gradient system defined by an o-minimal functions (leading to the smooth KL-inequality) and show that a similar process can be done for the co-derivative of the sweeping process map, whenever the latter is assumed to be o-minimal. This leads to the conclusion that bounded trajectories of a tame sweeping process have finite length. In particular, Kurdyka desingularization can be seen as a special case of the co-derivative desingularization

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#### Invited talk

# ON THE OPTIMAL CONTROL FOR THE LOCOMOTION OF RATE-INDEPENDENT SOFT CRAWLERS

#### PAOLO GIDONI

The inclusion of elastic components in the modelling and design of biomimetic crawlers endows these systems with new compliance capabilities, but at the same time raises additional challenges to the analysis of their locomotion properties. The framework of sweeping processes provides an effective framework to address such issues. In this talk, we introduce the optimal control problem for a family of such locomotion strategies. The most remarkable features of the problem are the dependence of the Bolza-type cost on the reaction of the constraints and the periodicity of the actuation.

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## Invited talk

# PROBLEMS WITH VIOLATED CLASSICAL INWARD POINTING CONDITION

#### NATHALIE KHALIL

We present some examples of state-constrained dynamical systems where the classical first-order inward pointing condition, known as Soner's condition, is violated. In these circumstances, the construction of trajectories satisfying the state constraint, termed feasible, fails. We show that under higher-order conditions, a novel construction guarantees the existence of feasible trajectories. We discuss also a result on neighboring feasible trajectories.

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## Invited talk

## ON THE OPTIMAL CONTROL OF BILEVEL SWEEPING PROCESSES

## FERNANDO LOBO PEREIRA

This presentation concerns some preliminary research on issues pertinent to the proper formulation of a certain class of a bilevel optimal control problems with dynamics specified by sweeping processes. A typical instance of this class of problems arises in the motion control of a "structured" crowd (of people, drones ir other vehicles) in a confined space. By a structured crowd, it is meant that the population is organized in subsets of individuals that remain within a certain bounded set and whose behavior satisfies specific dynamics and optimizes a specific performance criterion. The problem formulation and solution concepts are presented and discussed. Then, some of conditions under which the problem is proper or well-posed are discussed.

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#### Invited talk

## GLOBAL ASYMPTOTIC STABILITY OF PERTURBED SWEEPING PROCESSES

#### OLEG MAKARENKOV

In this talk we establish global asymptotic stability of perturbed sweeping processes with monotone perturbations. We consider both convex and prox-regular constraints. The sweeping process is periodic in the sense that both the constraint term and the perturbation term of the sweeping process are periodic in time. We show that the unique global solution is periodic or almost periodic according to whether the periods of these two terms are commensurable or not. Relevant results on global asymptotic stability are obtained in Tanwani, Brogliato, Prieur, SIAM J. Control Optim. 52 (2014). In the case of the proxregular sweeping process, our result appeared to be not capable to prove global asymptotic stability of periodic regimes in the crowd motion model (Cao-Mordukhovich, DCDS-B 22, 2017), but we provide another instructive example.

The results of the talk are joint projects with I. Gudoshnikov, M. Kamenskii, L. Niwanthi Wadippuli, and P. Raynaud de Fitte.

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#### Invited talk

# OPTIMAL CONTROL OF SWEEPING PROCESSES: CONSTRUCTION OF DISCRETE APPROXIMATIONS VIA Γ-CONVERGENCE

#### NGUYEN DINH HOANG

Techniques of discrete approximations which can be found in [3] are widely used under the study of optimal control problem of sweeping processes, see [1, 2]. In there, assumptions of Lipschitz type are assumed to guarantee the validity of strong convergence in both trajectories and its velocities. To adapt with applications in mechanics, in particular, hysteresis operators, via the use of  $\Gamma$ -convergence, we are able to weaken theses assumptions.

This is the joint work with Boris Mordukhovich.

## References

- G. COLOMBO, R. HENRION, N. D. HOANG AND B. MORDUKHOVICH, Optimal control of the sweeping process over polyhedral controlled sets, J. Diff. Eqs., Vol. 260 (1), 3397–3447, 2016.
- [2] N. D. HOANG AND B. MORDUKHOVICH, Extended Euler-Lagrange and Hamiltonian conditions in optimal control of sweeping processes with controlled moving sets., Journal of Optimization Theory and Applications, vol. 180, 1, pp. 256-289, (2019).
- [3] B. M. MORDUKHOVICH, Variational Analysis and Generalized Differentiation I, II, Springer, Berlin, 2006.

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#### Invited talk

# OPTIMAL MANAGEMENT OF PUMPED HYDROELECTRIC PRODUCTION WITH STATE CONSTRAINED OPTIMAL CONTROL

#### ATHENA PICARELLI

We present a novel technique to solve the problem of managing optimally a pumped hydroelectric storage system. This technique relies on representing the system as a stochastic optimal control problem with state constraints, these latter corresponding to the finite volume of the reservoirs. To deal with the problem in its full generality we follows the recent level-set approach presented in Bokanowski, Picarelli, Zidani, "State-constrained stochastic optimal control problems via reachability approach", SICON Vol.54(5) and we transform the original constrained problem in an auxiliary unconstrained one in augmented state and control spaces, obtained by introducing an exact penalization of the original state constraints.

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#### Invited talk

## CONSTRAINED MINIMAX CONTROL PROBLEMS

## GERALDO NUNES SILVA

Minimax control problems have been recently addressed in the literature in [1] and [2]. The first work provides necessary conditions of optimality in the form of the maximum principle for minimax problems without constraints. These results are then extended in the second work, where the proof method employed allows to include state constraints to the optimal control problem formulation. In this work we are able to obtain necessary conditions for mixed constrained minimax control problems under either: a) the constant rank assumption or the Mangassarian Fromovitz condition.

This is the joint work with Paola Geovanna Patzi Aquino.

#### References

- [1] D. Karamzin , et al., Minimax optimal control problem with state constraints, *European Journal of Control* 32: 24-31, 2016.
- [2] R. B. Vinter, Minimax optimal control, SIAM J. Control Optim., 44(3):939–968, 2005.

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#### Invited talk

## ON THE LYAPUNOV STABILITY OF SWEEPING PROCESS

## EMILIO VILCHES

The sweeping process is a first-order differential inclusion involving the normal cone to a moving set depending on time. Roughly speaking, a point is swept by a moving closed set. The sweeping process was introduced and deeply studied by J.J. Moreau (see [2, 3]) to model an elasto-plastic mechanical system. Since then, many other applications have been given, namely in, electrical circuits, crowd motion, hysteresis in elasto-plastic models, etc.

In this talk, we present a full characterization of nonsmooth Lyapunov pairs for perturbed sweeping processes under very general assumptions. As a consequence, we provide a criterion for weak invariance for perturbed sweeping process.

### References

- [1] A. Hantoute, E. Vilches: Lyapunov Pairs for Perturbed Sweeping Processes. Accepted for publication in Optimization Letters, 2018.
- [2] J.J. Moreau: Rafle par un convexe variable I. Exposé 15. Sém. Anal. Convexe Montpellier, pp. 1-43, 1971.
- [3] J.J. Moreau: Rafle par un convexe variable II. Exposé 3. Sém. Anal. Convexe Montpellier, pp. 1-36, 1972.
- [4] E. Vilches: Existence and Lyapunov Pairs for Perturbed Sweeping Process Governed by a Fixed Set. Submitted, 2017.

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Invited talk

## FULLY CONVEX BOLZA PROBLEMS WITH STATE CONSTRAINTS AND IMPULSES

#### PETER R. WOLENSKI

A Fully Convex Bolza (FCB) problem has the appearance of the classical calculus of variations Bolza problem

$$\min \int_0^T L(x(t), \dot{x}(t)) dt + \ell(x(0), x(T)),$$

where the minimization is over  $x(\cdot)$  belonging to some class of arcs. The distinguishing features of FCB are that the data  $L(\cdot, \cdot)$  and  $\ell(\cdot, \cdot)$  (i) may take on the value  $+\infty$  and (ii) are convex functions. Allowance of (i) provides great flexibility incorporating constraints so that most standard control problems come under its purlieu. However, broad generality is restrained by (ii), which although quite special, nonetheless includes the classical linear quadratic regulator and many of its generalizations. Furthermore, (ii) opens up the applicability of the tools of convex analysis.

We shall review the Hamilton-Jacobi (HJ) theory for FCB problems when the data has no implicit state constraints and is coercive, in which case the minimizing class of arcs are Absolutely Continuous (AC). When a state constraint  $x(t) \in X$  is added to the problem formulation, the dual variable may exhibit an impulse or jump when the constraint is active. The two properties of a state constraint and noncoercive data (which induce impulsive behavior) are in fact dual to each other, and the minimizing class becomes those of bounded variation. We shall describe Rockafellars optimality conditions for these problems and a new technique for approximating them by AC problems that utilizes Goebels self-dual envelope. The approximating AC problems maintain duality and the existing theory can be applied to them. It is proposed that an HJ theory can be developed for BV problems as an appropriate limit of the approximating AC problems. An explicit example will illustrate this.

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## Invited talk

# SENSITIVITY RELATIONS FOR SOME CONTROL PROBLEMS WITH STATE CONSTRAINTS

## HASNAA ZIDANI

In optimal control theory, it is well known that the costate variable of the Pontryagin principle can be interpreted in term of gradient of the value function, evaluated along the optimal state trajectory. This relationship is well established when the problem is without state constraints. In presence of state constraints, even very small perturbations of the optimal control can give trajectories that violate the constraints, and the value function is in general discontinuous. In this talk, we will discuss a general sensitivity result for some control problems with state constraints.

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