Course UTFSM 2014: Modelling and control of complex physical systems: the port-Hamiltonian approach

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1. Context

Complex heteregeneous technical systems (such as heterogeneous power sources and sinks in a distribution network or multiscale processes involving nano-, meso- and macro-scales in soft actuators) as well as biological systems (the metabolism in a cell for instance) represent a real challenge for engineering and applied mathematics. Indeed their dynamical behaviour seems to stem both from the particular network of interaction between their subparts as from highly nonlinear phenomena. It is for the moment still often not well understood how their dynamic behaviour emerges from these two types of properties. It is also still an open problem how to characterize mathematically such emerging dynamical properties but one promising way seems to be the use of the passivity properties of the subparts and of the interconnection network.

In Physics and Engineering such network systems are known and constructed since more than hundred years, for instance electrical circuits, hydraulic circuits or complex spatial mechanisms and were not only used as a technical devices but also as computing devices. Since the begin of the 20th century, the theory of analogies has been developed as a theory of these physical networks and has finally been formalized in a multi-physical modelling language called *Bond-graphs.*

Based on this physical network modelling language (which applies also to chemical reactions and biology), a physical systems theory has been developed in order to investigate the dynamical behaviour of these systems and the design control laws adapted to their structure. These mathematical models have been called *Port Hamiltonian systems.* These systems encompass actually both Hamiltonian systems as well as gradient systems but they are called *Hamiltonian* as they have a common underlying structure which is the geometric structure of Hamiltonian systems, called Poisson structure or Dirac structure. The term *port* indicates that the formulation encompasses the interface variables, called *port variables*, allowing to express the interaction of the system with its environment and being also the variables of the interconnection network.

The goal of this course is to introduce the Port Hamiltonian systems and present some of their dynamic properties as well as some methods to derive controllers that use their structure. The lectures intends to give a motivated introduction to the subject and will be based on numerous simple illustrating examples and exercise sessions along the lecture.

The **first module** of the course introduces the *Port Hamiltonian systems and some of their structural dynamical properties.* It starts with some brief reminder on the standard Hamiltonian systems as they stem from ideal mechanical systems before defining several generalizations corresponding to network models containing various physical domains and their topological constraint relations. The definition and existence of dynamical invariants of these systems are then analysed. The second part consists in defining the port variables and the port Hamiltonian systems corresponding to open physical systems able to exchange energy with their environment and to be composed through a interconnection network. Their systems properties in terms of dissipativity are analysed. The third part presents how to encompass irreversible phenomena, such as friction, in Port Hamiltonian systems in the following two ways. For isothermal systems, these irreversible phenomena may be described by a gradient-type dynamics; it will be shown how this may be embedded in the Port Hamiltonian framework. For non-isothermal systems, the (internal) energy or the entropy balance equation has to be considered and it will be shown how this changes the geometric structure of Port Hamiltonian systems.

The **second module** gives some methods to derive *controllers for Port-Hamiltonian systems* which use not only their passivity properties but shapes the system to a modified Port Hamiltonian system in closed-loop. In a first part it is shown how the storage function of a passive system may be related to the energy of a physical system and how this function can be used to design Lyapunov based controllers. The *energy shaping* approach is introduced, which consists on shaping the closed-loop energy function of a systems such that it defines a Lyapunov function with respect to a new closed-loop equilibrium. In a second part these concepts are specialized to port-Hamiltonian systems. First, the structural invariants, named Casimir functions, are characterized and it is shown how the Casimirs can be used to design energy shaping controllers. Then the idea is further developed in order to define a class of control that not-only shapes the energy of the closed-loop system but also its *geometric structure*. This method is called Interconnection and Damping Assignment - Passivity Based Control (IDA-PBC). Special emphasis and discussions will be devoted to the integrability conditions associated with the existence of closed-loop potentials (energy functions), and in the case of IDA-PBC to the matching condition arising from the equalization of the vector field defining the open-loop dynamic and the target vector field. It will also be shown, in the exercise sessions, how the method of characteristics can be used to find explicit (analytic) solutions to the matching equations.

The **third module** introduces the *extension of Port Hamiltonian systems to distributed parameter systems* such as flexible beams, plates or the water flow in canals and boundary control laws derived from its Hamiltonian structure. In a first part it presents the class of systems and various examples stemming from mechanics, fluid mechanics and thermodynamics are used to motivate the formulation. This class of port Hamiltonian systems can be expressed as Boundary Control Systems (BCS), which is an abstract formulation of partial differential equations with the control and observations at the boundary of their spatial domains. These abstract port Hamiltonian systems are defined on Hilbert spaces with the physical energy of the system being the norm of the space. It is shown that the well-posedness of the partial differential equation is directly verified by a matrix condition and furthermore, that for a large class of physical applications the problem is well-posed. This result comes from the natural natural definition of the inputs and outputs of a physical systems which generally imposes the “correct” boundary variables such that the mathematical problem is well-posed. The second part of this module deals with control. Constructive methods to asymptotically and exponentially stabilize these systems via boundary feedback are revised and interpreted in terms of passivity based control.

The case of dynamic boundary feedback is also be studied, i.e., the case of distributed parameter port Hamiltonian systems in feedback with a lumped parameter control system. It is shown under which conditions the control system asymptotically or exponentially stabilizes the interconnected system and how the structural invariants can be characterized and used to design energy shaping controllers.

The **fourth module** concludes with a return to the definition of *Port Hamiltonian systems as expressing systems of balance equations (* or *conservation laws with source terms* due to interactions with their environment). It aims at relating distributed parameter systems with localized parameter systems avoiding any spatial discretization scheme. In the first part a class of infinite-dimensional Port Hamiltonian systems is introduced which is defined using exterior differential forms as variables. It will be recalled that exterior differential forms are intrinsically related to integration in $\mathbb{R}^n$ and balance equations on conserved quantities. The canonical Dirac structure will be defined in relation with systems of two conservation laws as well as the Port Hamiltonian systems associated with it. In the second part it will be shown that considering a finite-dimensional spatial domain, defined by a graph or the complex associated to some meshing, a canonical Dirac structure may also be defined. The lecture will mainly concern the topology defined by a graph and derive different classes of Port Hamiltonian Systems for systems where dynamical subsystems are associated with the vertices, the edges or both. It will be illustrated with the examples of electrical circuits, spatial mechanical systems and diffusion phenomena.

2. Program and organization

The course will be held the between the **27-29 October, 2014** at Universidad Técnica Federico Santa María in Valparaiso, Chile. The course will be divided into 4 modules, it possesses an introductory level and is directed to students in engineering, physics and applied mathematics with interest in control. The course does not have specific prerequisites and the modules may be followed independently.

Each module consists of theoretical expositions and exercise sessions. The course will be supported by notes. The time-planning is the following.

	Monday 27/10	Tuesday 28/10	Wednesday 29/10
09:00 - 10:30	M1	M2	M3
10:30 - 11:00	Pause	Pause	Pause
11:00 - 12:15	M1	M2	M3
12:15 - 14:00	Lunch	Lunch	Lunch
14:00 - 15:30	M1	M3	M4
15:30 - 15:45	Pause	Pause	Pause
15:45 - 17:00	M2	M3	M4

2.1. M1: Port Hamiltonian models of open and dissipative physical systems (B. Maschke)

This module will introduce port-Hamiltonian systems (PHS) and their application to the modeling of multi-physical systems combining open mechanical, electromagnetic and thermodynamic systems. The topics treated in the module are:

- Introduction, definition and context in modeling, simulation and nonlinear control design.
- Hamiltonian formulation of models of conservative and dissipative multi-physical systems: a common structure to mechanical, electromagnetic and thermodynamic systems.
- Port-Hamiltonian formulation of open multi-physical systems, their properties and their composition.

2.2. M2: Passivity based control of PHS and IPHS (H. Ramirez and D. Sbarbaro)

This module will revise recently developed non-linear control theory based on the port-Hamiltonian framework. In particular Passivity Based Control (PBC), Interconnection and Damping Assignment - PBC (IDA-PBC) and the energy Casimir method. The detail of the module is the following:

- Explicit finite-dimensional PHS and their properties.
- IDA-PBC and Casimir methods for control with application to electro-mechanical systems.
- Control of Irreversible PHS (IPHS) and their application to chemical engineering.

2.3. M3: Control of distributed port-Hamiltonian system (Y. Le Gorrec and H. Ramirez)

This module presents an introduction to the control of distributed parameter PHS. Boundary control port Hamiltonian systems are defined and the conditions for existence of solutions stability are addressed.

- Boundary Controlled Port Hamiltonian Systems (BCPHS): a class of open distributed parameters systems.
- System and stability properties of BCPHS.
- Asymptotic and exponential stabilization via static and dynamic boundary feedback.

2.4. M4: PHS associated with discrete conservation laws (B. Maschke)

In this module we present an introduction to the structure preserving spatial discretization of infinite-dimensional PHS. It will be shown that it is possible to approximate the infinite-dimensional system by a set of finite dimensional PHS that preservers the total energy and the interconnection structure of the original system.

- Port Hamiltonian systems associated with systems defined on open graphs
- Port Hamiltonian formulation of discrete conservation laws

3. The speakers

Bernhard Maschke was graduated as engineer in telecommunication at the Ecole Nationale Supérieure des Télécommunications (Paris, France) in 1984. He received in 1990 his Ph.D. degree on the control of robots with flexible links and in 1998 the Habilitation to Direct Researches both from the University of Paris-Sud (Orsay, France). From 1990 until 2000 he has been associate professor at the Laboratory of Industrial Automation of the Conservatoire National des Arts et Métiers (Paris, France) and since 2000 he is professor in automatic control and vice-head of the Laboratory of Control and Chemical Engineering of the University Claude Bernard of Lyon, Lyon 1 (Villeurbanne, France). His research interests include the network modelling of physical systems, bond graphs modeling and control of physicochemical processes, port-Hamiltonian systems, irreversible thermodynamics, passivitybased control and control by interconnection, modelling and control of distributed parameter systems. He is member of the IFAC Technical Committee on Nonlinear Control since 2006 and the IFAC Technical Committee on Distributed Parameter Systems since 2011.

Daniel Sbarbaro received his Ph.D. from University of Glasgow, U.K. 1992 and the Electrical Engineering degree from the Universidad of Concepción, Chile, 1984. At the moment he is Professor of the Department of Electrical Engineering of the Universidad de Concepción. Among his functions, has been project manager in projects of technological transference for the great mining of copper. Additionally it has participated in active way in projects of investigation, Chileans and foreigners. Product of its investigation work, has published more than 100 articles, in international magazines and international conferences. All of them in areas of automatic control and instrumentation. His area of research is in Development of Non-linear control algorithms, Design of adaptive predictive control based on non-linear models, the design and applications of advanced controllers, the design of intelligent system and the use of multidimensional sensor for process control. Area of application: Mineral Processing and Energy systems.

Yann Le Gorrec was graduated as engineer in "Control, Electronics, Computer Engineering " at the National Institute of Applied Sciences (INSA, Toulouse, France) in 1995. He received in 1998 his Ph. D. degree from the National Higher School of Aeronautics and Aerospace (Supaero, Toulouse, France). His field of interest was robust control and self scheduled controller synthesis. From 1999 to 2008, he was Associate Professor in Automatic Control at the Laboratory of Control and Chemical Engineering of Lyon Claude Bernard University (LAGEP, Villeurbanne, France). He worked on modelling of physico-chemical processes, robust control, modelling and control of distributed parameter systems. From September 2008 he is Professor at National Engineering Institute in Mechanics and Microtechnologies. His current field of research is control of smart material based actuators, distributed micro systems and more generally control of micro actuators.

Hector Ramírez received the degrees in Electronic Engineering and Master in Engineering Science from the Universidad of Concepción, Chile in 2006 and 2009 respectively. In 2012 he received the Doctor degree in Engineering Sciences from the University of Concepción, Chile and the Doctor degree in Automatic Control from the University Claude Bernard - Lyon 1, France. He held a postdoc position at the department of Automatique et Systèmes Micro-Mécatroniques at FEMTO-ST, in Besançon, France. He is currently assistant professor at the University of Franche-Comté in Besançon and researcher at FEMTO-ST. His research concerns the modelling and control of complex physical systems using energy based approaches. More specifically, it focuses on the use of the framework of port-Hamiltonian system for the structural modelling and control of linear/nonlinear systems described by ordinary and/or partial differential equations arising from different physical domains. The main applications of his research activities are micro/nano-electromechanical and thermodynamical systems.