Summer School on

Port-Hamiltonian modelling and passivity-based control of physical systems. Theory and applications

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Scope

An emerging trend in control and robotic research seems to be the integration with different areas such as neuro-science, artificial intelligence or cognition. Nevertheless, it is still important to present basic and general methods, techniques and tools for the modeling, control and simulation of *physical systems* (e.g., mechanical, electro-mechanical and thermodynamical systems). This is even more fundamental for young researchers and scientists, which should have a solid knowledge and background of general approaches for dealing with multidisciplinar and complex systems. Examples in robotics of such systems are devices for advanced manipulation (dextrous hands), telemanipulation and haptic systems, cooperating robots and legged robots. These are *open systems*, i.e. devices that may be generically described as a system with a direct physical interface with its environment. It is important to note that the notion of open system naturally arises also in all the other energy domains, where an interaction among physical systems is present, domains which may seem very different from the electro-mechanical one.

It turns out that elegant and general mathematical tools for modelling and controlling interacting physical systems (also coming from different domains) exist, and that their use can be very helpful in solving complex problems, where other approaches may lead to more heuristic or confuse solutions. These methodological tools are framed in the *Hamiltonian* formalism. In particular, in order to describe and to manipulate these dynamical models in a systematic way, it is convenient to use a coordinate-free, geometric framework for their mathematical formulation, especially because of the intrinsic and strong nonlinearities in their system behavior. The framework of port-Hamiltonian systems, where the physical components are formulated as generalised Hamiltonian systems either in the lumped and in the distributed parameter case, and coupled to each other through power ports, will be presented in this Summer School. In this context, the resulting complex physical system can be geometrically described as a Hamiltonian system with respect to the geometric object of a Dirac structure.

Main goal of this Summer School is to present methods, techniques and tools for modelling and controlling complex interacting dynamical systems, using an integrated system approach allowing to deal with physical components stemming from robotics and also from different domains (e.g. electrical, mechanical, thermodynamic), both in the lumped-parameter and in the distributed-parameter case. To conclude, a general aim of this initiative is to explain in a clear and comprehensive manner the foundations of port-Hamiltonian system theory and of passivity based control. Concepts at the moment spread in a number of journal and conference papers are then illustrated in a compact and

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integrated form. This will allow to the audience to get the basic concepts and, if interested, to rapidly being able to access the state-of-the-art in this field.

Course program

The course is organised into five main topics, briefly presented below. Each argument requires an half-day class.

- **Passivity and passivity-based control.** This initial part aims at illustrating the basic ideas and results of passivity-based control. Once the intuition behind the concept of passivity / dissipativity is discussed together with the main definitions, the relation between passivity-based control and Lyapunov stability is discussed. Then, stabilisation by output feedback and via interconnection (e.g., small-gain) is presented.
- **Port-Hamiltonian modelling.** The class of port-Hamiltonian systems, that are a particular type of passive systems, is presented starting from the basic concepts on physical modelling, i.e. on bond-graphs. The key geometric features (e.g., invariants and Dirac structures) are discussed in the lumped paramenter case, and the extension of the classical port-Hamiltonian system theory towards the description of irreversible processes is discussed. This latter point leads to the definition and characterisation of the class of irreversible port-Hamiltonian systems.
- **Control of port-Hamiltonian systems.** This part of the course is devoted to control synthesis within the port-Hamiltonian framework. The starting point is the general theory of passivity-based control, that leads to simple control schemes based on damping injection and on energy-balancing. More powerful control schemes that are able to exploit the port-Hamiltonian structure to obtain stability in closed-loop are also discussed. Among them, main emphasis is given the control techniques that rely on generalised canonical transformations, and on interconnection and damping assignment passivity-based control (IDA-PBC). Finally, basic results on the control of irreversible port-Hamiltonian systems are illustrated.
- **Infinite dimensional port-Hamiltonian systems.** This topic deals with the extension of the port-Hamiltonian formalism presented so far to the distributed parameter case, i.e. to systems described by PDEs. The classical formulation of an infinite dimensional port-Hamiltonian system derived from conservation laws is discussed and, for a class of system with one-dimensional domain, the key results on boundary control are illustrated. Finally, a brief overview on spatial discretisation techniques within the port-Hamiltonian framework are also presented.
- **Port-Hamiltonian systems in robotics.** In this conclusive part of the course, the applications of port-Hamiltonian modelling and control to the field of robotics is presented. In particular, the use of port-Hamiltonian modeling and control for the control of interaction of robotic systems (both fixed and aerial robots) will be discussed. The concept of energy tank is introduced, and its use in teleoperation of swarms of aerial vehicles is described. Finally, an overview of the future directions of port-Hamiltonian systems in robotics will is provided.

The speakers

Alessandro Macchelli took the Laurea Degree cum laude and the PhD in Automatic Control and Operational Research at the University of Bologna (DEIS) in 2000 and 2003. He has been visiting scholar (sponsored by the NACO2 Project) at the University of Twente in 2001 and Post-Doc in 2003. In 2004, he got a Post-Doc position at the University of Bologna (DEIS), and in 2005, he joined DEIS as assistant professor in robotics and industrial automation. After 2005, he has been visiting professor at the Tongji University in Shanghai, at the Institute of Automatic Control and Control Systems Technology of the Johannes Kepler University Linz, at the National Engineering Institute in Mechanics and Micro-Technologies (FEMTO-ST/AS2M) in Besaçon, and at the Institute of Cyber-Systems & Control of the Zhejiang University in Hangzhou. His research activity is focused on port-Hamiltonian systems, with particular emphasis on modelling, simulation and control of distributed parameter systems, and applications of the port-Hamiltonian framework to robotics and mechatronics. He is currently author of more than 50 journal and conference papers on these topics.

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 1986 until 1990 he prepared his Ph.D. on the control of robots with flexible links at the Department of Advanced Robotics of the Commissariat à l'Énergie Atomique. From 1990 until 2000 he has been an Associate Professor at the Laboratory of Industrial Automation of the Conservatoire National des Arts et Métiers (Paris, France), and since 2000 he is a Professor in Control Engineering at the Laboratory of Control and Chemical Engineering of the University Claude Bernard of Lyon (Villeurbanne, France). His research interests include the modelling and control of multi-physical systems, port-Hamiltonian systems, passivity-based control and modelling and control of distributed parameter systems.

Cristian Secchi received the M.Sc. degree in computer science engineering from University of Bologna, Bologna, Italy, in 2000. He received the Ph.D. degree in information engineering from University of Modena and Reggio Emilia, Modena, Italy, in 2004. He is an Associate Professor with the University of Modena and Reggio Emilia. Dr. Secchi's Ph.D. thesis was selected as one of the three finalists of the 5th Georges Giralt Award for the best Ph.D. thesis on robotics in Europe. He participated to the CROW project, selected as one of the finalists for the 2010 EUROP/EURON Technology Transfer Award for the Best Technology Transfer Project in Europe. He is an Associate Editor for *IEEE Robotics and Automation Magazine* and he is currently an Associate Editor of *IEEE Transaction on Robotics* and of the *IEEE Robotics and Automation Letters*. His research interests include humanâĂŞrobot physical interaction, tele-robotics, mobile robotics, and surgical robotics. He has published more than 100 papers on international journals and conferences.

Stefano Stramigioli received the M.Sc. degree *(cum laude)* from the University of Bologna, Italy, and the Ph.D. degree *(cum laude)* from the Delft University of Technology, The Netherlands, in 1992 and 1998, respectively. He is currently a Full Professor of advanced robotics and Chair Holder with the Robotics and Mechatronics (formerly Control Engineering) Group, University of Twente, Enschede, The Netherlands. He has more than 150 publications, including four books, book chapters, and journal and conference contributions. Prof. Stramigioli is the Emeritus Editor-in-Chief of the *IEEE Robotics and Automation Magazine,* which he left as the journal in the field of robotics with the highest impact factor (3.0). He is a member of the Editorial Board of the Springer journal *Intelligent Service Robotics,* and he is currently the Vice President for Member Activities of the IEEE Robotics and Automation Society (RAS). He has been an Administrative Committee member of the IEEE RAS. His interest lie in modeling and control of robotic systems by energy-based methods.