Special Section on Symbolic Methods for Complex Control Systems

THE increasing complexity associated with many modern engineering applications, including autonomous robot guidance and navigation, process control in sensor-rich environments, and control of biological systems, has far-reaching implications for control system design. As an example, reactive, embedded software systems, interacting among themselves and remote users over communication networks, introduce a whole new set of system-level challenges, and classic control design objectives such as stability, performance, and robustness are being complemented with a number of new questions. These include the cost of hardware implementation, measured for example not only by computational requirements such as speed and memory, but also by communication requirements such as available communication bandwidth. Moreover, the complexity associated with specifying the control procedures and with verifying the behavior of the closed-loop system increasingly plays a fundamental role, especially in safety-critical control systems arising in energy and transportation networks, and in medical applications.

During the last decade, significant progress has been made toward addressing these issues and overcoming the complexity associated with such novel control tasks. This complexity stems from a number of sources, including the complexity of the task itself, the complexity of the system dynamics, and the complexity of the environment in which the system is deployed. An emerging approach to address the complexity issue is to decompose the control task into a finite collection of building blocks, or modes of operation. As a result, control procedures are no longer solely thought of as mappings from sensory data to actuator signals, but rather as sequences of tokenized instructions that contain descriptions of such mappings. Throughout this Special Section in the IEEE TRANSACTIONS ON AUTOMATIC CONTROL, we hope to highlight some of these recent results, and illustrate how a number of new control system analysis and design problems can be properly addressed at the level of symbols rather than signals.

The general area of "Symbolic Control" has been developed under the banner of "Hybrid Systems." Such systems are systems that are influenced and characterized by models with both discrete and continuous components, from switched linear systems to full-scale hybrid automata. A number of results have emerged in this area with a classic control-theoretic flavor, including optimal control, stability, system identification, observers, and well-posedness of solutions. However, a new line of research in hybrid systems has also been launched that studies issues not quite standard to the controls community, including formal verification, abstractions, model expressiveness, computational tools, and specification languages. These latter results belong to the class of results that we refer to as symbolic control, and what makes them different from the first class of problems is that they address questions at the highest level, i.e., at the level of symbols, and as such draw on tools from computer science and discrete mathematics as much as on classic control theory. At the same time, they provide faithful descriptions of the continuous level performance of the actual system, and as such, provide a formal bridge between the continuous and the discrete.

When we began working on this Special Section, in the spring of 2004, our goal was to provide an accessible survey of state-of-the-art, as well as point out promising future research directions. In fact, as the area of symbolic control has been gaining momentum, a number of technical challenges have been addressed (and to a certain degree resolved), all focusing on better understanding and design of continuous signal to finite symbol mappings. These include abstracting continuous dynamics to symbolic control descriptions, instruction selection and coding in finite-bandwidth control applications, and applying formal language theory to the continuous systems domain. We are quite happy with the response from the community, and all of these issues are present in some form in this Special Section.

Two of the papers in this Special Section study the problem of control using strings of symbolic control instructions, sometimes referred to as motion description languages, maneuver automata, or control quanta. In particular, Bicchi *et al.* considers the problem of generating (in polynomial time) reference trajectories for dynamical systems using a symbolic representation of the available inputs. Andersson and Hristu-Varsakelis address a similar issue in a slightly more applied setting, and a method is proposed for generating sequences of symbolic feedback control laws for mobile robots navigating in unknown environments.

The paper by Tabuada looks at the problem of producing finite models of continuous systems, by constructing models that contain only a finite number of the possible trajectories. The question that is addressed is then to what extent such simplified (or abstracted) models can be used to control the original system. Delvenne and Blondel assume that such a useful, abstracted model has been obtained, in order to characterize the complexity associated with the controller itself. In particular, the main result concerns the generation of estimates of the minimal complexity that a controller needs to exhibit in order to solve certain point-to-point transfer problems.

Another subarea of symbolic control is to use symbolic, discrete methods for characterizing and/or improving the continuous-level behavior of the system. This line of thought is represented by two papers in the Special Section. The paper by Habets *et al.* focuses on the problem of synthesizing control laws for piecewise- affine hybrid systems on simplices. The paper proposes a solution to this problem based on the control-to-facet

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problem at the continuous level, and on dynamic programming at the discrete level. In Bemporad and Giorgetti, logic/symbolic methods are used for accelerating and improving the performance of numerical solutions to optimal control problems. In particular, hybrid numerical/symbolic solution techniques for finite-horizon optimal control problems are considered.

In Klavins *et al.*, the symbolic aspect of the control procedures stand out clearly since that paper introduces a formal grammar for governing self-assembly processes. The main idea is to let grammatical rules describe the interactions that can occur between two or more individual parts upon contact. Through this formalism, algorithms are proposed for solving self-assembly and self- organization problems.

As a final remark, it should be noted that this Special Section (or any special issue/section for that matter) only represents a particular snapshot of the field and there are undoubtedly areas and results that are not included in this section. Although we made every effort to include every aspect of the symbolic controls field, we cannot claim that the coverage is complete.

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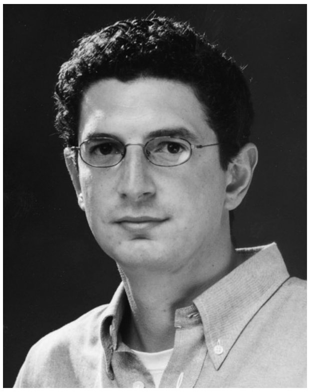

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