

Research Challenges in Advanced Controls

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1. Introduction

This white paper sets out some views on the research challenges in the area of advanced controls. It was prepared for Unit C3 on “Embedded Systems” of IST. Therefore, the exposition is given with a “bias” towards research directions likely to have a substantial impact on embedded system design and analysis.

The views expressed in this document are personal and reflect the opinion of certain members of the COLUMBUS consortium but not necessarily the host organisations.

2. Major Research Challenges

Novel Applications: In recent years control has been moving beyond its traditional applications to electro-mechanical systems, chemical processes etc. New and exciting applications are being investigated in a range of areas:

1. Transportation.
2. Communication networks.
3. Quantum systems.
4. Biomedical systems.

In parallel, more traditional applications such as automotive, avionics and power networks have been approached from an entirely new perspective. The traditional control approach has been to decompose the system into manageable components and develop control algorithms for each separate component. Recently, these large-scale systems have been approached more from a networked and embedded system perspective. Advanced control methods are being developed to address the system as a whole, dealing with all the problems that arise out of the complexity of the system, its distributed nature, the networked interactions of the components, etc.

All these applications have posed new challenges for control theory. In the rest of this section we highlight some of these challenges that require the development of new advanced control methods.

Hybrid System modelling: Many different frameworks have been proposed for modelling embedded and hybrid systems. The different frameworks were developed to address different problems and therefore have different merits. For example, some are geared more towards analysis, others towards simulation and others towards design. Some allow composition and abstraction operations (needed, for example, to build large scale models for distributed and networked systems) while others aim more for descriptive power, to allow one to model a wide range of physical phenomena.

To address this fragmentation, there is a need to develop precise semantics for the different modelling frameworks to allow one to

1. Systematically capture and reason about the real time properties of the models.
2. Translate models from one framework to another, to exploit the different advantages that the different frameworks have to offer.

A related issue is the need for systematic methods for developing models for large-scale systems. Until now large scale systems have been modelled in a rather ad-hoc way, using the designer intuition about the process. This approach may no longer be feasible, especially for novel applications such as quantum and biomedical systems where physical intuition often fails. Systematic model identification methods need to be developed to address this problem.

Computational tools: Despite numerous theoretical developments on methods for controller synthesis for hybrid systems, the impact of these methods in applications is not as substantial as it could and should be. Part of the reason for this is the lack of computer-aided-design tools. Even though powerful tools are available for certain classes of hybrid systems (e.g. MLD systems and timed automata), for many problems of interest to applications (e.g. reachability problems when the continuous dynamics are nonlinear) tool support is rather limited; for emerging classes of systems (e.g. stochastic hybrid systems) tool support is virtually non-existent. In addition, much of the tool development effort has been fragmented, with different research teams creating their own tools to support specific design methods. The tools are based on different modelling languages and often attempt to address different types of problems (simulation, model checking, model predictive control, etc.) Therefore, there is also a need to develop some form of tool interchange format. The idea is to allow designers to create a common model of the system they are interested in and then analyse the model using a number of different tools in an integrated framework, thus avoiding long and tedious translations from one formalism to another and from one CAD system to another.

In all cases explored so far, the limitation of the tools, when they exist, is of computational nature: the computational cost of the numerical algorithms involved is high so that the complexity of the systems that can be treated is below what is requested for most industrial applications of importance.

Dealing with uncertainty: In many of the applications highlighted above, one has to deal with uncertainty in the form of un-modelled dynamics, process and sensor noise etc. In addition, many important classes of embedded systems (e.g. automotive, power and communication networks and transportation) involve distributed, hierarchical, multi-agent systems or systems with humans in the loop. For such systems, uncertainty also enters the process through the actions of human operators, the actions of agents in the system whose intentions are unknown or partially known, etc. Therefore, methods are needed for modelling, simulation analysis and synthesis for systems involving such uncertainty. To date there are very few approaches to this problem and none that is systematic enough to deal with systems

of a realistic size. One possibility is stochastic hybrid systems, i.e. systems that involve the interaction of discrete, continuous and probabilistic dynamics.

Implementation-aware control: Control algorithms when implemented on an embedded platform often lose their theoretical properties due to a number of non idealities that the platform carries. For example, limited communication resources create delays that are unpredictable before implementation that can invalidate stability results. Limited computing resources force to carry out the computation required by the control algorithm with approximations that may invalidate the correctness of the controlled system actions. Hybrid systems are a way of dealing with a holistic view of the problem since the controller can be modelled as a discrete system and the plant with a continuous-time system thus allowing us to consider the effect of the limitations of the controller on the overall behaviour of the controlled system. In addition, the controller implementation itself can be designed so that the control algorithms requirements are taken into account. This interlaced approach, called platform-based control design, has been tried in some of the applications to transportation systems (e.g., UAV control and automotive control), but in an ad hoc fashion. A systematic methodology, well-founded algorithms and related tools for design of embedded controllers will have great impact in making advanced control of strategic importance to industry.

3. Key players in the area

Disclaimer: my views on this topic are clearly biased because of my personal research preferences. I do not include for example teams doing excellent work on nonlinear or optimal control, because in my view their work is not directly related to embedded systems.

I firmly believe that all teams involved in the COLUMBUS project are doing outstanding work in the area of advanced controls. These teams are the University of Cambridge, University of L'Aquila, University of Patras, INRIA-IRISA and PARADES.

Other teams doing excellent research in this area around Europe are (in no particular order) ETH Zurich, Linköping, Lund and KTH in Sweden, T.U. Eindhoven and University of Twente in Holland, Leuven and Louvain-la-Neuve in Belgium, University of Dortmund, University of Pisa and Siena in Italy, VERIMAG and INRIA in France. Teams doing related work with an eye towards robotics are those of Mechanical Engineering at NTUA in Greece and the University of Porto in Portugal.

4. Other Programmes

To the best of my knowledge there is no programme dedicated exclusively to advanced controls in the U.K. The Engineering and Physical Sciences Research Council (EPSRC) are, however, funding a number of projects in this area. Most are under their "Control, Optics and Electronics" thematic area in the "Engineering Research Programme". Contact points are Vicky Jones or Elisabeth Hylton. Assessing the total budget dedicated to advanced controls by the EPSRC is difficult from the publicly available data.

The situation appears to be similar in France, Greece and in Italy, with the Directorate General on Research and Technology (GGET) for Greece and the National Science Foundation for Italy playing the role that EPSRC plays in the U.K. Recently, the Italian Ministry of University and Research (MIUR) has funded a Center of Excellence on Embedded Control at the University of L'Aquila. Regarding Sweden, the different funding

programmes (SSF and Vinnova) support the theme “signals and systems” (which includes advanced control) in a significant way, with Linköping, Lund, and KTH as centers of excellence.

By contrast, in the U.S. there are numerous funding agencies supporting advanced control research. In recent years, DARPA and the NSF have dedicated entire programmes to this area e.g. the Software Enabled Control (SEC) programmes and the recent NSF Information Technology Research (ITR) programme. Related research has also been supported by the Army Research Office (ARO) and the Office of Naval Research (ONR). This may partly explain the relative dominance of the U.S. researchers in the areas of embedded and networked systems in recent years.