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Author(s):
Kouvelas, Anastasios

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Adaptive Fine-Tuning for Large-Scale Nonlinear Control Systems

by
Anastasios Kouvelas

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Despite the continuous advances in the fields of control and computing, the design and deployment of an efficient Large-scale Nonlinear Traffic Control System (LNTCS) remains a significant objective. This is mainly due to the complexity and the strong nonlinearities involved in the modeling of the traffic flow process. Practical control design approaches are often based on simplified models about the system dynamics, leading to LNTCS with suboptimal performance, as the use of more complex models of effective LNTCS is virtually unavoidable in most complex control system applications.

The ultimate performance of a designed or operational LNTCS (e.g. urban signal control, or ramp metering) depends on two main factors: (a) the exogenous influences, e.g. demand, weather conditions, incidents, and (b) the values of some design parameters included within the LNTCS. When a new control algorithm is implemented there is a period of, sometimes tedious, fine-tuning activity that is needed in order to elevate the control algorithm to its best achievable performance. Fine-tuning concerns the selection of appropriate (or even optimal) values for a number of design parameters included in the control strategy.

Moreover, the continuous medium- and long-term variations of the traffic system dynamics call for a frequent or even continuous maintenance of LNTCSs. When an operational but "aged" control algorithm needs to be updated the same fine-tuning procedure has to take place, which – if done properly – is extremely costly. Typically, this fine-tuning procedure is conducted manually, via trial-and-error, relying on expertise and human judgment and without the use of a systematic approach. Currently, a considerable amount of human effort and time is spent for initialization or calibration of operational LNTCSs, which does not always lead to a desirable outcome. In many cases, the result is that system maintenance is neglected and the system performance deteriorates year after year.

This dissertation introduces and analyzes a new learning/adaptive algorithm that enables automatic fine-tuning of LNTCS, so as to reach the maximum performance that is achievable with the utilized control strategy. The proposed Adaptive Fine Tuning (AFT) algorithm is aiming at replacing the conventional manual optimization practice with a fully automated online procedure. The dissertation provides a detailed analysis of the algorithm as well as a step-by-step application description. Finally, application results of the algorithm to real-time fine-tuning problems of general LNTCS are presented, using both microscopic and macroscopic simulation environments.

The efficiency and online feasibility of AFT algorithm is investigated through extensive simulation experiments for two LNTCS. The first test case is a large-scale ramp metering control problem. A multivariable ramp metering regulator is applied to a stretch of the Monash motorway in Melbourne, Australia, using the macroscopic simulation tool METANET. The latter test case corresponds to the application of an urban signal control strategy to the road network of Chania, in Greece, using the microscopic commercial simulation tool AIMSUN. In both simulated cases, AFT is used in order to iteratively fine-tune the design parameters of the system. The simulation results illustrate the algorithm's efficiency and real-time applicability. AFT is seen to provide efficient automatic fine-tuning of the design parameters of general LNTCS, guaranteeing safe and convergent behavior.

The main contributions of this research include:

- The development and presentation of AFT methodology.
- The mathematical analysis of the proposed algorithm and discussion of its relation to other known stochastic approximation methodologies.
- A thorough investigation (via simulation experiments) of the algorithm's efficiency and feasibility under different problems and scenarios.
- The provision of general guidelines about the application of AFT to general large-scale fine-tuning problems.

The thesis is organized in a series of self-contained chapters as following:

- Chapter 1 is an introductory Chapter that presents the motivation and the thesis goals.
- Chapter 2 presents a short overview of automatic control methods. Optimization and control techniques that provide optimal control strategies are discussed, as well as the open-loop and closed-loop optimal control regulators. Finally, the need for fine-tuning in large-scale, complex control systems applications is described.
- Chapter 3 presents the state of the art in parameter estimation/optimization methodologies. It provides an analytical presentation of Stochastic Approximation (SA) and analyzes the general principles of designing SA search algorithms. Also, the popular SA algorithms FDSA, RDSA and SPSA are thoroughly described.
- Following, Chapter 4 explores the AFT algorithm. Moreover, it presents a comparison of the use of theoretical/simulation-based methods and adaptive and neural/learning methods as a solution to the fine-tuning problem. The concept of universal approximators is also discussed. Finally, the Chapter presents efficient techniques about calculating stepsizes for SA methods.
- Chapter 5 presents the application of AFT algorithm to a large-scale ramp metering problem. AFT is applied to the Monash motorway in Melbourne, Australia and the macroscopic simulator METANET is used for the simulation experiments. This Chapter examines and analyzes in details the results of the simulation experiments.

- Chapter 6 presents the application of AFT algorithm to a large-scale urban signal control problem. AFT is applied for fine-tuning to the urban road network of the city of Chania, in Greece and the microscopic simulator AIMSUN is used for the simulation experiments. This Chapter examines and analyzes in details the results of the simulation experiments.
- The thesis is concluded with Chapter 7, which summarizes the findings and results. Finally, future perspectives are presented, which can help to the extension of these results.

In summary, the dissertation presents an original algorithm that delivers a theoretically founded and practically valuable method and tool for the significant fine-tuning problem that arises in countless ITS field installations and could lead to sensible improvements, independently of the specific algorithm fine-tuned (see conference publications [3, 5, 6] and journal publications [1, 2, 4] for more details). It should be emphasized that parts of this PhD dissertation analysis and results provide the background for a currently running field installation of AFT for the network-wide traffic signal control in Chania, Greece, within the European FP7 project AGILE (http://www.agile-fp7.eu).

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