Model-Free Controller Design based on Simultaneous Perturbation Stochastic Approximation

Dissertation

Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Informatics

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Abstract

Recently, with the rapid growth in science and engineering, most of the real-world process plants have been built on a large scale and complex systems. As a consequence, modeling of such systems may become very difficult and require a lot of effort. Therefore, it is necessary to develop a control method that does not depend on plant models, which is known as the model-free control approach. At the same time, it is also worthy to consider an optimization tool for the model-free approach that is simple to understand for engineers and can optimize a large number of control parameters in a fast manner. So far, there have not been enough literatures to discuss the application of model-free control schemes for the above demands.

Motivated by the above background, a model-free control scheme is considered in our study. Here, a simultaneous perturbation stochastic approximation (SPSA) algorithm is suggested as a promising tool for the model-free control approach. Then, this dissertation focuses on assessing the effectiveness of the SPSA-based algorithm for various model-free control problems such as PID tuning of MIMO systems, optimizing fuel consumption of hybrid electric vehicles, and maximizing power production of wind farms.

Firstly, we present a performance comparison of SPSA-based methods for PID tuning of MIMO systems. In particular, four typical SPSA-based methods, which are one-measurement SPSA (1SPSA), two-measurement SPSA (2SPSA), global SPSA (GSPSA), and adaptive SPSA (ASPSA) are examined. Their performances are evaluated through extensive simulation for several controller design examples, in terms of stability of the closed-loop systems, tracking performance, and computation time. In addition, the performance of the SPSA-based methods is compared to the other stochastic optimization based approaches.

Secondly, we propose a model-free controller design for hybrid electric vehicle systems. Here, a switching control scheme is adopted, where each sub-controller is specified for each driving condition, in order to improve the fuel efficiency. An SPSA-based method is utilized to optimize a large number of design parameters in the switching controller. The design method is applied to the JSAE-SICE benchmark problem, which is developed using GT-SUITE of Gamma Technologies, Inc. and integrated with Simulink / MATLAB. The effectiveness of the proposed

controller is evaluated in terms of the fuel efficiency improvement and driver's satisfaction, as compared to the sample controller of the benchmark problem.

Finally, we provide a model-free approach for maximizing power production of wind farms. Based on the information on the wind farm configuration, such as the turbine location and wind direction, we propose a multi-resolution SPSA (MR-SPSA)-based method that can achieve fast model-free controller tuning. In order to evaluate the effectiveness of our proposed scheme, a wind farm model with dynamic characterization of wake interaction between turbines is used and then the proposed method is applied to the Horns Rev wind farm. Furthermore, the performance of the MR-SPSA-based method is also compared with other existing model-free methods, in terms of maximum power production and convergence time.

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Symbols and Definitions

In this thesis, we use the following symbols and definitions. The symbols $\mathbb{R}$ and $\mathbb{R}_+$ represent the set of real numbers and the set of positive real numbers, respectively. The symbol $\mathbb{S}^{n\times n}$ denotes the set of $n\times n$ positive definite matrices. The cardinality of set $\mathcal{S}$ is denoted by $\mid \mathcal{S} \mid$. The vector whose all elements are one is denoted by $\mathbf{1}$. For the vector $\boldsymbol{\theta}$, we use $\parallel \boldsymbol{\theta} \parallel$ to express the standard Euclidean norm. For the random variable V, the probability of event $V = a$ is represented by $\mathbb{P}(V = a)$. The expectation of the random variable b is denoted by $\mathbb{E}(b)$. For $\delta \in \mathbb{R}_+$, $\mathrm{sat}_\delta : \mathbb{R}^n \to \mathbb{R}^n$ denotes the saturation function whose i-th element given as follows:

$$\text{The } i\text{-th element of } \mathrm{sat}_\delta(\boldsymbol{\theta}) = \begin{cases} \delta & \text{if} \quad \delta < \theta_i \\ \theta_i & \text{if} \quad -\delta \leq \theta_i \leq \delta \\ -\delta & \text{if} \quad \theta_i < -\delta \end{cases}$$

where $\boldsymbol{\theta} \in \mathbb{R}^n$ and $\theta_i \in \mathbb{R}$ is the i-th element of $\boldsymbol{\theta}$.