Knowledge-Based Systems 98 (2016) 55–67

Contents lists available at ScienceDirect

Knowledge-Based Systems

journal homepage: www.elsevier.com/locate/knosys

Local linear regression for efficient data-driven control

Danilo Macciò*

Institute of Intelligent Systems for Automation, National Research Council, Via de Marini 6, Genova 16149, Italy

ARTICLE INFO

Article history:
Received 18 March 2015
Revised 1 October 2015
Accepted 23 December 2015
Available online 4 January 2016

Keywords:
Data-driven control
Local linear regression
Statistical learning theory

ABSTRACT

The problem of data-driven control (DDC) represents an important topic in the area of automation, due to the availability of large amount of data generated by the production processes occurring in industrial plants. The aim of this work is the study of an efficient DDC approach for nonlinear dynamic systems that exploits the data directly coming from the plant. In this framework, the control problem consists in the design of an automatic regulator able to execute a task by using the data collected during the successful operation of the plant, regulated by a reference controller such as a human operator. The proposed synthetic regulator is based on local linear regression models chosen for their simplicity of training and efficiency in incorporating new data generated by the plant. The conditions under which the derived controller converges to the optimal one are analysed in the context of statistical learning theory, which provides an appropriate framework to efficiently address this kind of DDC problem. Simulation results involving a dynamical system are provided to show the properties of the proposed method in an applicative context.

1. Introduction

One of the most important research topics in the area of automation is represented by data-driven control (DDC), i.e., the possibility of regulating a system through a series of measurements of its input–output variables of interest. This problem has got particular relevance during the last decade, since modern plants in electronics, machinery, chemical industry, transportation, have become significantly more complex. This makes the application of the traditional control designs based on physical laws impractical. Furthermore, the production processes generate and store huge amount of data that contain all the relevant information necessary to the design of the controllers, the prediction of the state variables, the analysis of the performance, the diagnosis of the faults. Due to the importance of the problem, a great variety of approaches have been proposed in the literature to address this problem. Such approaches differ primarily as to the way in which they employ the data and the assumptions made on the structure of the controller. Concerning the data usage, we can distinguish among methods based on on-line data, on off-line data and those based on both; regarding the design of the regulator, we have DDC methods that preassign a controller structure and methods with unknown controller structure (the reader interested in a brief description of the most popular DDC techniques can consult [27]). All the aforementioned methods have in common the fact that the controller must operate in closed-loop, ensuring the stability of the system by applying stability methods typical of automatic controls. However, the hypotheses the system must fulfil are quite strong and this makes the application of these methods difficult in many practical cases.

The present work considers an instance of DDC from another point of view, namely, in the case the designer must exploit the data coming from the successful operation of a complex plant, in order to derive a synthetic controller able to perform a given task or to reach a given goal. This amounts to the problem of learning the experience of some reference controller, such as a human operator, which executes a particular task efficiently and acts as a teacher for the automatic regulator. In the case the plant is not subjected to a highly time-varying dynamics and the control signal implemented by the reference operator is sufficiently well-behaved, the synthetic controller should be able to perform the task and reach the goal in the same way as the teacher or it could provide support to him. Notice that this formulation of DDC does not require any particular hypotheses on system, such as controllability or observability, since we have from the data that the operator is always able to reach the goal using the available control.

Since the DDC analysed involves the construction of a regulator able to emulate a reference controller, a suitable framework to formalise the problem is Statistical Learning Theory (SLT), which contains the techniques and methodologies necessary to address

* Tel.: +39 0106475835; fax: +39 0106475600.
E-mail address: danilo.maccio@cnr.it, ddmach@ge.issia.cnr.it

http://dx.doi.org/10.1016/j.knosys.2015.12.012

this particular type of DDC setting. With such a formulation, the first issue to address is the definition of a suitable class of models where we look for the best approximation of the reference controller. For the problem at hand we need a set of functions able to efficiently incorporate new information coming from the plant, since the data generation process is typically continuous, requiring a periodic retuning of the controller. Then, classical parametric models such as neural networks, splines, radial basis function are not practical in the present case, since the computational burden required to find the optimal parameters are time consuming. On the contrary, methods based on non-parametric regression are more suited for the approximation of the reference controller. In this work, we investigate the use of local linear regression to approximate the behaviour of the reference controller on the basis of the available data. This structure approximates the target function by solving a separate least squares problem at each evaluation point, suitably weighted by means of kernel functions. In general, the main advantage of this regression method is that the only parameter to be optimised is the smoothing parameter of the kernel functions (sometimes called *bandwidth*), leading to a computationally efficient training procedure. Thanks to this fact, local linear regression turns out to be convenient in addressing the learning approach for the DDC analysed in this work, since updating the optimal bandwidth in case additional information is available is a very simple task.

In conclusion, this work proposes a technique based on local-linear regression methods to derive an automatic controller starting from a set of measurements relative to the considered plant. In addition, a convergence analysis of the synthetic regulator to the behaviour of the real operator is provided using the framework of SLT, with the aim of discussing the properties that the functions involved must possess in order for the learning procedure to be consistent.

The paper is organised as follows. Section 2 deals with work related to DDC, pointing out the differences among the methods addressed in the literature and the proposed technique. In Section 3 the problem of DDC is formalised in a SLT context and local linear regression models are accordingly described. Section 4 contains an analysis of the convergence properties of the proposed method, whereas in Section 5 a simulation example shows in practise the performance of the introduced DDC problem. Finally, Section 6 concludes the work.

2. Related works

The DDC is an approach widely studied in the past decades, since the application of classical control schemes based on physical laws or on simulation and approximation of the cost function is unfeasible in several contexts. In particular, it is not always possible to employ methods based on reinforcement learning or approximate dynamic programming [4,8,35], or online/adaptive techniques specifically designed for a task such as tracking, or relying on a particular architecture of the controlled system [26,28,36].

The most popular DDC methods merely approximate the system dynamics with the aim of deriving a control law that ensures stability of the closed loop, while in our framework we make use of samples from a reference control already present (the reader interested in such traditional approaches can consult [14,20,21,38] and the references therein). Furthermore, the method we propose does not assume any particular condition on the plant while in the aforementioned references the system has a fixed structure and the only control task addressed is tracking; in the present approach the system simply acts as a source of data for learning problem, and the goal of the control is not necessarily tracking.

The issue of storing the experience acquired by an operator is a theme widely studied and analysed in the literature, to list a few [1,3,15,31,33,37]. Notice that this topic is characterised by different names, such as skill learning, human control, behavioural cloning, learning by imitation, with respect to the context it belongs (e.g., robotics, aircraft control, gaming, tactics, etc). All these references have in common the use of a machine learning models to store the behaviour of the reference controller; examples of popular models are neural networks, support vector machines, decision trees. These methods differ from the method studied in this work for the presence of function approximators that require non-trivial optimisation procedures, that make difficult to incorporate new data coming from the plant. The issue of using new available data is addressed by the proposed approach making use of local linear regression models, whose optimisation procedure is fast and efficient.

It is worth noting that local linear regression models have already been employed successfully in the DDC framework in the more traditional cases, that is, when the data are used to approximate the system or when the aim of the controller is to follow a reference signal in a closed loop design (see, e.g., [2,5,14,32]). The present work considers the problem from another perspective, since the aim of this formulation is to store directly the experience of a reference controller, rather than approximating the system dynamics or controlling the system in a closed-loop design. Such formulation of DDC is justified by the fact that Data Collection Systems (DCSs) are nowadays very common in industrial plants and, due to the increasing size of storage devices, allow to store a huge amount of information, which can be employed in the design of a regulator.

An approach that makes use of tools typical of statistical learning is considered in [29], where the control function is approximated by means of Nadaraya–Watson models. These type of approximators are easy to implement and the optimisation procedure is computationally efficient, since they require only the assignment of an appropriate one-dimensional parameter. However, it is known (see, e.g., [23]) that Nadaraya–Watson models exhibit poor accuracy in the approximation of the objective function at the boundary of the input domain. These border effects greatly restrict the applicability of these estimation methods, especially in cases where the control function varies rapidly and the input dimension is high. In the simulation section, the proposed method, based on local linear regression, is compared to the one analysed in [29], that makes use of Nadaraya–Watson models.

3. Statement of the problem and local linear regression

This section is devoted to the formal description of the DDC framework analysed in the context of the present work and describes the local linear regression models employed to address it. More specifically, in the first part of the section the learning formulation of the problem is presented, then, the local linear regression structure used to approximate the reference controller is described.

3.1. Learning from a reference controller

The aim of the DDC block is to learn the experience of some reference teacher through a set of data, in order to derive an automatic controller of the system under consideration. In this regard, it is necessary to address the following three issues: (i) the mathematical model of the systems that will be taken into consideration; (ii) the formal description of a reference controller; (iii) the structure of the data that will be used for the design of the synthetic regulator.

Concerning (i), since DCSs systems are digital devices, i.e., they store the data with a given sample rate, we consider a discrete-time model evolving according to the following