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Approximate model predictive building control via machine learning

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HIGHLIGHTS

- The construction of approximate model predictive control laws (MPC) is presented.
- Easy implementation of advanced control strategies suitable for low-level hardware.
- Multivariate regression and dimensionality reduction algorithms are used.
- Simulation case study employing temperature control in a six-zone building.
- Simplified control laws retain most of the performance of the original MPC.

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ABSTRACT

Many studies have proven that the building sector can significantly benefit from replacing the current practice rule-based controllers (RBC) by more advanced control strategies like model predictive control (MPC). However, the optimization-based control algorithms, like MPC, impose increasing hardware and software requirements, together with more complicated error handling capabilities required from the commissioning staff. In recent years, several studies introduced promising remedy for these problems by using machine learning algorithms. The idea is based on devising simplified control laws learned from MPC. The main advantage of the proposed methods stems from their easy implementation even on low-level hardware. However, most of the reported studies were dealing only with problems with a limited complexity of the parametric space, and devising laws only for a single control variable, which inevitably limits their applicability to more complex building control problems. In this paper, we introduce a versatile framework for synthesis of simple, yet well-performing control strategies that mimic the behavior of optimization-based controllers, also for large scale multiple-input-multiple-output (MIMO) control problems which are common in the building sector. The approach employs multivariate regression and dimensionality reduction algorithms. Particularly, deep time delay neural networks (TDNN) and regression trees (RT) are used to derive the dependency of multiple real-valued control inputs on parameters. The complexity of the problem, as well as implementation cost, are further reduced by selecting the most significant features from the set of parameters. This reduction is based on straightforward manual selection, principal component analysis (PCA) and dynamic analysis of the building model. The approach is demonstrated on a case study employing temperature control in a six-zone building, described by a linear model with 286 states and 42 disturbances, resulting in an MPC problem with more than thousand of parameters. The results show that simplified control laws retain most of the performance of the complex MPC, while significantly decreasing the complexity and implementation cost.

1. Introduction

The total energy used in heating, cooling, ventilation and air-conditioning (HVAC) systems in commercial and residential buildings nowadays accounts for 40% of the global energy use [1]. Numerous studies reported that advanced HVAC control could significantly reduce the energy use and mitigate emissions of greenhouse gases, see, e.g. [2–4]. However, currently, the majority of the building control strategies adopt simple rule-based logic with only limited energy saving capabilities [5,6].

One of the control methods exploiting the full potential of the building's HVAC systems is model predictive control (MPC) [7]. The

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high performance of MPC is achieved by minimizing the energy use and maintaining high comfort standards while taking into account technological restrictions, weather forecasts and building dynamics. In MPC, control inputs that minimize a certain objective function (which accounts for energy use and thermal discomfort) subject to constraints are computed by solving a corresponding optimization problem at each sampling instant. In recent years, many energy efficient MPC approaches have been reported for control of HVAC systems [8–14], household's hot water systems [15,16], or incorporate demand response objectives [17,18].

Despite this intensive research efforts, the transfer of this technology to the commercial sector is still in its early stages, mainly because of the following four reasons as pointed out by [19]. First, an accurate yet simple building model is required. However, obtaining such well-performing model with a minimum of effort is a difficult and time-consuming task [20]. As a promising solution, in recent years a methodology for the automatic synthesis of a global model of a building and its equipment based on exploiting ontology-based Building Information Models (BIM) has been proposed [21,22]. Second, design and tuning of MPC controllers are challenging, because the commission engineers are usually not trained to set up such complex control systems based on numerical optimization. Moreover, contrary to the industrial applications of MPC, buildings are not operated with on-site engineers monitoring and supervising the functioning of the employed control system. For these reasons, there is a strong request in this field for a simple implementation of the control algorithms without loss of their high energy efficient performance [23]. Third, there is also a strong need for data availability and processing power as the computation of MPC control actions for complex systems can be easily based on hundreds or even thousands of parameters/states. These variables are provided either by direct real-time measurements from the network of sensors, by external services like weather forecasts, or by state estimators. And fourth, the on-line solution of the corresponding optimization problem and the extensive data processing impose considerable challenges on hardware and software infrastructure, which is not a standard in today's buildings.

Although some approaches for a fast and simple on-line implementation of MPC for building control applications have been suggested previously [24,25], the task remains very challenging, especially when using existing control hardware, such as programmable logic controllers (PLC). There are two main difficulties. First, such a simple hardware provides only limited computational capabilities with a limited amount of memory storage (typically in the range of kilobytes). Second, most PLCs do not allow the control algorithm to be implemented in high-level languages. As a result, implementation of the complex, optimization-based control algorithms on a simple hardware is cumbersome [26].

The ambition of this paper is to tackle the last three challenges from the list of issues by constructing a simple, yet well-performing, control policy that offers a smooth implementation suitable for low-level hardware. One approach for achieving this goal is to calculate the explicit representation of the MPC feedback law [27,28]. For a rich class of MPC problems, the explicit solution takes the form of a piecewise affine (PWA) function defined over a polyhedral domain of the parametric space. Obtaining the optimal control input then reduces to a mere function evaluation. Such a task can be easily performed, even by a simple hardware [29], and can be extended e.g. to stochastic MPC formulations [30]. The fundamental limitation of explicit MPC solution, however, is that the complexity of the computed PWA control law grows exponentially with the dimensionality of the parametric space imposed by prediction horizon and number of variables. Therefore it can be applied only on the hardware with storage capacity large enough to accommodate the PWA function. However, this is usually not a realistic assumption, since the size of explicit MPC solutions can easily exceed several megabytes even for systems with low complexity, making it infeasible for complex building control problems with several thousands of parameters.

An alternative way to tackle this problem is to employ approximations of the MPC solution. The central idea here is not new. In fact, a variety of approximate explicit MPC solutions has been proposed in the literature [31]. In general, there are two groups of approaches. The first group is represented by geometric methods that are based on an efficient polyhedral partitioning of the state space [32–34]. The second group consists of data-driven function approximation methods. The earliest work in this area was based on neural networks [35], while more recent works based on e.g. PWA [36], polynomial [37], and nonlinear [38] function approximations, or wavelet interpolations [39] have been reported as well.

One of the first attempts for the approximation of MPC laws in the building control context was introduced by [40]. This method is based on linear interpolations of MPC solutions generated for a grid of selected parameters. However, the complexity of such grid approach is increasing exponentially with the number of parameters, which strongly limits its applicability to large scale problems. Other researchers [23,41,42] used classification algorithms for extracting simple decision rules from MPC employing logical control actions. Approaches approximating the continuous control laws are also available, e.g., based on piecewise linear mixing architecture [43] or nonlinear regression employing Hammerstein-Wiener models [44]. The approximation of the continuous MPC laws via enhanced regression trees, with piecewise linear approximation, was presented in [45]. All the approaches listed above were developed and tested only on problems with modest complexity, usually with single (continuous or binary) control variable, and with only dozens of parameters.

Moreover, only few of these papers give an increased attention to the feature engineering (FE) process. However, due to the strong influence of the features on the performance of the trained model, FE is considered to be a fundamental part of almost any practical machine learning application [46]. The gains from using only the most relevant features are threefold: first, improved performance, second, reduced complexity, and third, improved interpretability of the developed models. This is, however, typically where most of the effort in a machine learning project goes, learning is often the quickest part [47]. Engineering features properly is primarily a manual, difficult and time-consuming task, mostly because it is domain-specific, while learners can be largely general-purpose. Additionally, each type of the model will respond differently to different types of engineered features [46]. Therefore, one of the holy grails of machine learning is to automate the feature engineering process [47]. For these reasons a substantial research interest has appeared in recent years into the development of the feature learning algorithms, see, e.g. [48,49], or advanced semi-automated feature engineering systems [50]. The main drawback of these methods, however, is that the physical meaning of the original features is lost. This is a significant drawback in our case, as we are interested in the selection of the most relevant features as a subset of the original feature vector, without the loss of their physical meaning. For this task several feature selection (FS) methods suitable for building energy models are available in the literature nowadays. In [51] authors presented a heuristic approach tailored for support vector machine (SVM) models, while in [52] a statistical Wald's test has been used for identification of irrelevant features for neural network (NN) models. However, the search for all relevant features is, in general, an NP-hard problem [53].

In this paper, we propose a compact methodology for the construction of simple suboptimal MPC-like control strategies for building control applications by using advanced machine learning algorithms. The focus is on the creation of a systematic and universal framework applicable to a variety of large-scale building control problems, while providing valuable insights into the selection of the most relevant features and appropriate type of approximation model. We investigate two multivariate regression algorithms. First, we use regression trees (RT), where the approximation of the control law is given as a binary tree.