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Data-driven predictive control for demand side management: Theoretical and experimental results

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Abstract

Demand side management is vital for secure and efficient operations in energy systems with increasing renewable energy use. Current modeling and control methods lack scalability for widespread application. This paper introduces a new signal matrix model predictive control (SMM-PC) algorithm. This method offers stochastic forecasts that account for both disturbances and measurement inaccuracies with minimal parameter adjustments, thus enhancing reliability through likely constraint fulfillment. Its efficacy is thoroughly benchmarked against three advanced algorithms in a space heating scenario using a precise simulator. These findings are corroborated by real-world tests on the system replicated by the simulator. To test versatility, the algorithm is also applied to varied systems such as a residential water heater and a stationary battery. Simulations indicate that the SMM-PC algorithm can increase constraint adherence and energy savings by up to 90% and 8%, respectively, when compared to other data-driven strategies. Experimental outcomes further verify its adaptability across different demand side management tasks, with consistently solid control performance in all cases.

Figure 1. Overview of case studies (left) and physical facility for experimental verification (right).

Introduction

While the increasing penetration of renewable energy resources contributes to mitigating climate change, the intermittency in their production is expected to significantly challenge the energy system operation. Meanwhile, the International Energy Agency estimates that one billion households and eleven billion smart appliances could actively participate in demand response programs globally by 2040 [1], which can be seen as a subcategory of demand side management (DSM). This opens up the possibility of applying active DSM on a large scale to cope with the surge of renewable energy, as well as facilitating energy conservation and improving the occupants' comfort. In the existing literature, model predictive control (MPC) has been viewed as a promising control strategy to enable DSM. For example, MPC is used to provide distributed coordination of buildings to support flexible energy infrastructure operation. However, due to the large number of heterogeneous controlled systems, first-principles modeling approaches cannot ensure timely and cost-effective implementation. In fact, modeling often takes up the majority of the budget in applying model-based control, in terms of both time and cost. Therefore, data-driven control methods have recently received considerable attention. This work addresses this challenge by developing a novel data-driven control algorithm and systematically assessing its performance across heterogeneous components in simulation and experimental studies.

In this work, a novel indirect data-driven predictive control framework, dubbed signal matrix model predictive control (SMM-PC), is presented. SMM-PC is first proposed with maximum likelihood prediction. Reliable stochastic prediction under noise is later provided, which is very difficult to obtain in other data-driven methods. On the other hand, stochastic MPC approaches have been widely studied in the literature and applied in the building sector, and guarantee high-probability constraint satisfaction by enforcing chance constraints. Similar techniques can be applied to stochastic data-driven predictors.

The contributions of this work are threefold. Firstly, the existing SMM-PC algorithm is extended to explicitly account for disturbances and measurement noise by incorporating the stochastic control framework with chance constraints. This algorithm provides a disciplined yet easy-to-implement approach to achieve reliable operation with data-driven methods under various uncertainties. Secondly, the performance is extensively analyzed by comparing multiple state-of-the-art data-driven algorithms using a high-fidelity simulator for space heating (SH) control. Results demonstrate that the proposed stochastic SMM-PC algorithm not only satisfies operating constraints more reliably than competing methods, but it also reduces energy consumption at the same time. In addition, experiments have been carried out to validate the controller's performance on the same facility on which the simulator has been built. Lastly, the transferability is experimentally evaluated across different types of controlled systems, including a domestic hot water (DHW) heating system and a stationary electric battery. It is demonstrated that the SMM-PC algorithm is easily transferable to different types of controlled systems with satisfactory performance since there are very few tuning parameters involved. An extended version of this manuscript can be found in [2].

1. Approach towards Flexibility and Business Experiences and success stories

A series of numerical and experimental case studies have been carried out to evaluate the performance and transferability of the stochastic SMM-PC algorithm. The studies, summarized in Figure 1, consider transferability across heterogeneous controlled systems, transferability from simulation to experiment, and the impacts of certain control tasks.

Three controlled systems were investigated: a space heating system, a DHW heating system, and a stationary Lithium-ion electric battery, representing typical demand-side resources. All the system configurations and data presented in the rest of the paper are based on the NEST building located at Empa in Switzerland, shown in Figure 1. Typical control tasks include constrained resource planning and trajectory tracking. In the building sector, constrained resource planning is prevalent and aims to minimize total energy consumption while ensuring constraint satisfaction. Reference tracking tasks can also be formulated for the stationary electric battery, as it is considered to be a promising candidate for ancillary service provision through tracking reference signals set by system operators.

Space heating The system considered in this study is a three-room apartment, hereafter referred to as the UMAR unit. Each room was treated as one thermal zone and heating power was dissipated into the zones through constant volume radiant ceiling panels. The continuous power setpoint, determined by the controller, was realized by regulating the valve opening, which was converted into discrete opening and closing sequences using pulse-width modulation logic. Additionally, the control of space heating was subject to constraints imposed by occupants' perception of comfort. Although other indoor conditions also influence occupants' comfort, temperature sensors are the most commonly available for assessment, so thermal comfort bounds were expressed as temperature limits in this study. As the unit is residential, the thermal comfort bounds were predefined, considering the unit to be unoccupied during the day and occupied during the night. The definition led to relaxed temperature constraints during unoccupied hours. Specifically, the constraints were set to be between 20°C and 26°C from 08:00 to 16:59 and between 22°C and 24°C from 17:00 to 07:59 of the second day.

Various approaches have been proposed in the literature to compare control algorithms for space heating, ranging from a simulation-only approach using a hypothetical physics-based model to an experiment-only approach with a placebo comparison. The latter requires two identical physical systems running different control algorithms in identical conditions, which is rarely possible in reality. Other studies employ a degree-day metric, in which average boundary condition (e.g., ambient temperature) is considered, neglecting other factors such as heat gains. In this work, we first benchmarked control algorithms on a high-fidelity white-box model of the physical system. The model was based on detailed knowledge of the system layout and the heat storage and transfer characteristics of the construction materials. Additionally, the model was calibrated with three-year field measurements at a 1-minute temporal resolution, capturing both the dynamics of the physical system and the heat gains due to occupants. Due to the high model fidelity, a high level of confidence in the expected control performance can be ensured. The transparency and reproducibility of the results are ensured by providing the model in an open repository. An experimental study was then conducted to evaluate constraint satisfaction with Algorithm 1 using the signal matrix model.

Domestic hot water heating Energy consumption of DHW is taking an increasing share of the total energy consumption, especially for newly-constructed and renovated buildings with better-insulated envelopes. DHW is often equipped with a water buffer tank for hydraulic decoupling and reducing the load diversity factor. Energy scheduling needs to guarantee sufficient hot water storage within the tank and a minimum temperature constraint of 45°C was considered. Additional periodic temperature boosting to the level of 60°C is necessary to avoid Legionella contamination. In this work, temperature boosting once per week was considered by introducing a step change in the lower temperature limit. The water tank has three temperature sensors vertically distributed along the tank wall, and the measurements differ due to stratification. In the experiment, the average measurement was considered. Lastly, due to high uncertainties associated with individual occupants' water draw activities, a persistence forecast of water draw was implemented using the most recent weekly water draw patterns.

Stationary electric battery Stationary electric batteries are increasingly popular in the residential sector due to the large mismatch between rooftop solar production and the residential load pattern. Such electricity storage can be used for arbitrage in the electricity market through constrained energy scheduling and for stabilizing power system frequency through reference tracking. Since no standard evaluation metric and use case can be found in the literature, two simple artificial case studies were considered. In the first case study, the amplitudes of battery charging and discharging power were minimized while guaranteeing that the state-of-charge was maintained within the predefined dynamic limits. Since the limits varied over time, knowledge of the future system response was necessary. In the second case study, the battery's charging and discharging powers were controlled such that its SOC followed a reference signal. Although classical PID control schemes also excel at reference tracking and the future system response is not crucial to consider, this case study was carried out to cover all possible applications.

Figure 1. Overview of case studies (left) and physical facility for experimental verification (right).

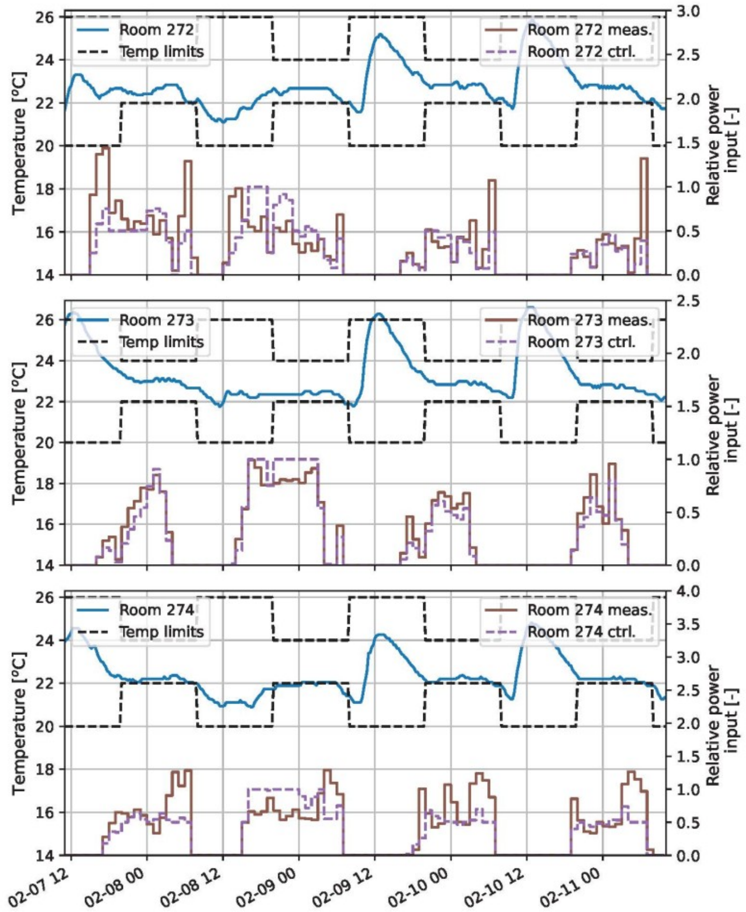

Figure 2. Experimental results of space heating control. Top plot: results for Room 272. Middle plot: results for Room 273. Bottom plot: results for Room 274. The dashed black curves show temperature limits. The solid blue curves show temperature trajectories. The dashed purple curves show controller decisions (scale at left). The solid olive curves show realized thermal power inputs into the rooms in relative terms by normalizing using thermal power capacities (scale at right).

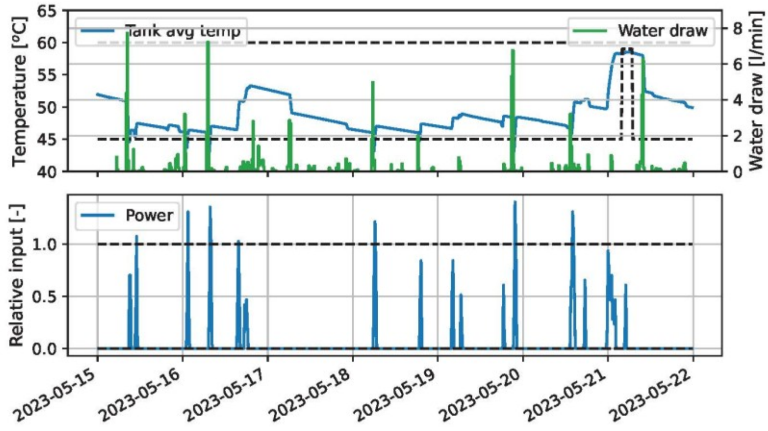

Figure 3. Experimental results of controlling domestic hot water heating. Top plot: the solid blue curve shows the average tank temperature trajectory and the dashed black lines indicate temperature limits (scale at left). The solid green curve shows the actual water draw profile (scale at right). Bottom plot: the solid blue curve shows the measured thermal power into the tank and the dashed black lines indicate expected thermal power limits. The maximum power varies depending on supply temperature.

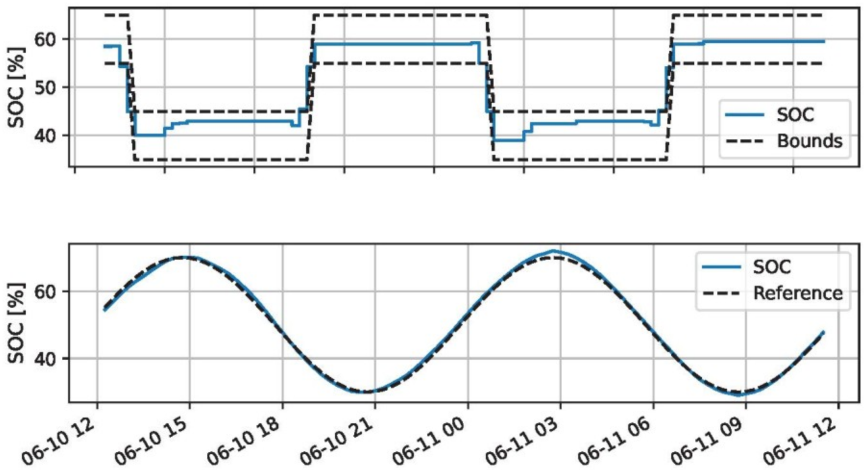

Figure 4. Experimental results for the control of an electric battery. Top plot: resource planning task. Bottom plot: reference tracking task. The solid blue curves show the actual SOC. The dashed black lines indicate temperature limits for the top plot and the reference trajectory for the bottom plot.

2. Added Values/Conclusion

Space heating The experiment was carried out between February 7 and February 11 of 2023. During the experiment, the prediction horizon and the confidence level of constraint satisfaction were set to be 15 (3.75 h) and 0.7, respectively. They were the same as the values used in the simulation study. The experimental results summarized in Figure 2 include temperature measurements, control decisions, and realized power inputs into each temperature zone. Different from the numerical study, the actuation of control decisions is subject to errors in practice, leading to mismatches between control decisions and realized power inputs in Figure 2. It can be observed that the temperature in each room was maintained within the predefined comfort zone most of the time. The accumulated constraint violations in Rooms 272, 273, and 274 are 0.025 °Ch, 2.159 °Ch, and 1.518 °Ch, respectively. Additionally, in all rooms, preheating decisions can be observed once the step increase of the lower temperature limits was within the horizon of the controller. The results validated the hypothesis that SMM-PC is able to ensure constraint satisfaction within the technical capability of the underlying physical system.

Domestic hot water heating The experimental results of DHW heating control are summarized in Figure 3, where both water draw and average tank temperature time series are shown together with predefined temperature limits. It can be observed that average tank temperatures were mostly maintained within the predefined limits. The accumulated constraint violation over one week was observed to be 3.9 °Ch. Since the control task was to minimize energy consumption, the tank temperature was kept close to the lower limit leaving only necessary hot water, which contributed to reducing heat loss through the tank wall. A large constraint violation was observed when the step change of the lower temperature limit occurred due to decontamination. This was due to the large uncertainty level in the water draw activities and the narrow feasible bound during decontamination, which resulted in the infeasibility of the tightened constraints. In other words, the data-driven algorithm was not able to guarantee high-probability constraint satisfaction with the available data. In this case, it is recommended to relax the output constraints and/or to include more data on the water draw activities to provide data-driven load forecasts.

Stationary electric battery The experimental results of the electric battery control are shown in Figure 4 for both the resource planning task and the reference tracking task. The resource planning results show that the SOC of the battery was maintained within the limits, verifying the constraint satisfaction hypothesis. The accumulated constraint violation was 15.95 %h. Since the SOC limits were artificially designed, the accumulated constraint satisfaction value was not a crucial performance indicator. In this experiment, a high confidence level of 0.95 was used, so the actual SOC profile appeared to be conservative, and the trajectory stayed in the middle of the predefined zone to actively avoid constraint violation. The results of the reference tracking experiment show remarkable precision; in fact, the root mean square error between the reference signal and the actual SOC is only 0.79 %. To put it in context, the measurement quantization error is 0.5 %. Both experiments confirm the applicability of SMM-PC to typical control tasks for electric batteries.

Scalable modeling and control frameworks can facilitate demand side management, a critical tool for the reliable and efficient operation of future energy systems. To address current limitations, this work proposes a novel data-driven predictive control algorithm using the signal matrix model. By using a stochastic control framework, this algorithm is designed to be reliable against noise and disturbances. The performance of the methodology is comprehensively evaluated in high-fidelity simulations by comparing it against other data-driven predictive control approaches, and its transferability is validated in multiple experimental studies. Two main conclusions can be drawn from the quantitative results. Firstly, compared to the state-of-the-art data-driven predictive control algorithms, the proposed algorithm can improve occupants' thermal comfort and energy savings by up to 90% and 8%, respectively. Secondly, the algorithm effectively ensures constraint satisfaction, and its performance can be transferred to other systems with minimal tuning effort. Therefore, the proposed algorithm can facilitate large-scale deployment of demand side management to support energy system operation. To conclude, several limitations must be noted. First, while data-driven approaches provide scalability, the interpretability of the decisions still needs to be assessed. Poor interpretability could potentially compromise the security of a system comprising many automated and distributed devices, which are aggregated to support secure grid operation in the first place. Second, while the transferability across different controlled systems was evaluated, it remains to be assessed for the same type of controlled systems with different characteristics. For example, the proposed algorithm needs to be tested on a large group of heterogeneous buildings with different heating input systems.

References

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[2] M. Yin, H. Cai, A. Gattiglio, F. Khayatian, R. S. Smith, and P. Heer, "Data-driven predictive control for demand side management: Theoretical and experimental results," *Applied Energy*, vol. 353, p. 122101, Jan. 2024, doi: 10.1016/j.apenergy.2023.122101.