Multiple Time-scale Model Predictive Control for Thermal Comfort in Buildings

Rachel K. Kalaimani
University of Waterloo
rachelpsg@gmail.com

Srinivasan Keshav
University of Waterloo
keshav@uwaterloo.ca

Catherine Rosenberg
University of Waterloo
cath@uwaterloo.ca

ABSTRACT

Intelligent control of heating, ventilation, and air conditioning (HVAC) systems in commercial buildings have been extensively studied in the literature. Although prior work has shown the benefits of using Model Predictive Control (MPC), existing work falls short either by relying on linear HVAC models or using MPC assuming control actions at a single (hourly) time scale, although more frequent control is feasible for some HVAC elements. Our main contribution is the use of a bi-linear thermal model and the careful modeling of the multiple time-scales inherent in the operation of an HVAC system, which permits the design of a multiple time-scale MPC control. We find that employing a multiple time-scale MPC results in significantly better comfort in comparison to a single time-scale MPC, typically without an increase in power consumption. Moreover, there exist cases where there is a significant reduction in power consumption (40%) for the two time-scale MPC in comparison to the single time-scale, with no decrease in comfort.

1. INTRODUCTION

A heating, ventilation, and air conditioning (HVAC) system aims at ensuring thermal comfort and maintains appropriate indoor air quality for the occupants inside a building. HVAC systems are major contributors to the carbon footprint of most developed nations. Thus, there is a strong need for improvements in HVAC efficiency especially in commercial buildings. Traditional HVAC systems employ simple controls such as ON/ OFF control or Proportional Integral Derivative (PID) control. These methods are not energy efficient [5]. Hence recent research has focused on advanced control strategies for operation of HVAC systems that reduce the energy consumption without necessarily compromising occupant comfort.

The thermal model of an HVAC-controlled room is inherently bi-linear. Traditionally, this model is linearized about an operating point of the supply air temperature to develop an optimal controller using approaches such as linear quadratic control or fuzzy logic [4]. However, this linearization is valid only in the neighborhood of an operating point, reducing performance when the system deviates from it. More recent work uses a non-linear system model [1, 6] combined with Model Predictive Control (MPC) [3]. In this approach, at each time step an optimal control action is computed using forecasts of the system behavior. An MPC can also handle constraints on states and control inputs, which is not possible with traditional control techniques.

Our major contribution is to combine a non-linear thermal model with a two-time scale MPC f or optimizing energy consumption of an HVAC system in a building. This matches both the thermal dynamics and the different time scales of operation of the different components of the HVAC system.

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2. SYSTEM & ASSUMPTIONS

We consider a commercial building with one zone with n identical rooms. The air handling unit (AHU) supplies air at a specified temperature with an appropriate humidity level. The supply air temperature cannot be changed frequently because this can damage the HVAC components [2]. Thus, we assume that this value can be changed only once every hour. The variable air volume (VAV) unit controls the rate of flow of air from the AHU to the rooms, enabling additional control of temperature in the rooms. Unlike the AHU, the VAV's control can be changed fairly often. We change this value once in 10 minutes in our model of the system. To save energy, instead of heating or cooling outside air, some of the air from the room is recirculated and mixed in with outside air in the mixer. The ratio of the air that is reused is also a control variable. Since this is a control parameter inside the AHU unit, we change this once every hour. The HVAC system ensures that the temperature of each room is within a comfortable range when occupied. We make the following assumptions:

1. The thermal model of the room is a lumped parameter model. That is, each room is considered as a single point and we are interested in the temperature at this point.
2. Each room is assumed to be thermally isolated from others, i.e., there is no heat transfer across the rooms.
3. Accurate forecasts of outside air temperature and occupancy pattern of each room are available.
4. The occupancy status of each room, the temperature in each room and outside temperature are measured

and made available to the control system in HVAC once every 10 minutes.

3. OVERVIEW OF THE CONTROLLER

In a conventional MPC, a time horizon is fixed and then, for each intermediate time step, all control values are recomputed. Specifically, these values are the supply air temperature u, the volume of air flow v, and the ratio of re-use air r. In our case, due to the different time-scales, only some of the optimal values are updated at each 10-minute time step. This modified MPC is described next.

- We fix the forecast horizon to be of 24 time steps or 4 hours ($24 \times 10/60$).
- At the beginning of each instance of the MPC, we obtain forecasts for occupancy and outside temperature, for an horizon of 24 time steps.
- Each time step, we compute
  - The VAV control value v.
  - If the time step lies on a hour boundary, then also the AHU temperature u and the remix control value r

In this way, v may change at a faster time scale than u and r. Hence, comfort requirements are likely to be better satisfied than with hourly control. For example, if the rooms were not occupied in the beginning of an hour, then, with hourly control, any occupancy that happens later in the hour would not be taken into account until the beginning of next hour, causing the occupants some discomfort. Symmetrically, if the rooms become unoccupied during the hour, then the energy spent on providing a thermal comfort for the remaining time in that hour could be saved. We observe precisely these effects in our numerical evaluation.

Note that using a bi-linear thermal model results in a non-convex optimization problem.

4. RESULTS AND CONCLUSION

We use energy use and comfort as the two metrics to compare our approach with the state of the art. The first metric is the energy consumed by the HVAC system to provide the appropriate thermal level, and the second metric measure the degree to which the temperature of each room is maintained within a certain range whenever the building is occupied. Using these metrics, we compare our two time-scale MPC with a model which is representative of the state of the art. Specifically, compared the following two systems:

1. S1 : The system is controlled by a single time-scale MPC at the time scale of one hour.
2. S2 : The system is controlled by our two time-scale MPC where the VAV can be modified every 10 minutes.

We compared S1 and S2 using real occupancy traces (that we collected in an academic office building) for 70 representative days. We observed that the power consumption was nearly the same for both systems for most of the days, but S1 often failed to meet comfort requirements. An example case is in Figure 1. There were a few days where S2 had higher power consumption (more than 10%) than S1 but the performance of S1 with respect to comfort was very poor. There were also a handful of situations where there was significant reduction in power consumption in S2 when compared with S1. Hence, we observe that S2 essentially offers better comfort than S1 for the same amount of energy.

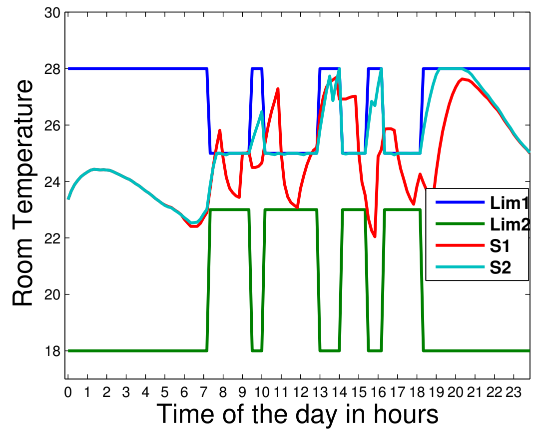

Figure 1: Room temperature for S1 and S2. Lim 1 and Lim 2 refer to the desirable comfort range based on occupancy.

To conclude, our preliminary investigation has revealed that by using a bi-linear thermal model and employing a two time-scale MPC as the control approach results in significantly better comfort compared to a single time-scale MPC, and typically without an increase in power consumption. Our approach for HVAC control, therefore, appears to be a promising direction for future work.

5. REFERENCES

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