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Testing and demonstration of model predictive control applied to a radiant slab cooling system in a building test facility

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ABSTRACT

Radiant slab systems have the potential to significantly reduce energy consumption in buildings. However, control of radiant slab systems is challenging. Classical feedback control is inadequate due to the large thermal inertia of the systems and heuristic feed-forward control often leads to unacceptable indoor comfort and may not achieve the full energy savings potential. Model predictive control (MPC) is now attracting increasing interest in the building industry and holds promise for radiant systems. However, an often-cited barrier to its implementation in the building industry is the high computational cost and complexity relative to the feedback controls used in conventional systems. The objectives of this study were to (i) verify the correct operation of an open source MPC toolchain developed for radiant slab systems, and (ii) demonstrate its efficacy in a test facility. A matched pair of cells in the FLEXLAB building test facility at the Lawrence Berkeley National Laboratory was used in the study. The proposed MPC toolchain was implemented in one cell and the performance compared to that of the other cell, which used a conventional heuristic control strategy. The results showed that the simplified MPC approach applied in the toolchain worked as expected and realized energy savings over the conventional control strategy. The MPC yielded 42% chilled water pump power reduction and 16% cooling thermal energy savings, while maintaining equal or better indoor comfort.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems account for about 44% of the total energy use in U.S. buildings [1]. The energy consumption of HVAC systems has been shown to be sensitive to the quality of the control; enhanced control strategies can yield savings of 2%–16% [2] while incorrect control and other control-related faults can increase consumption by ~10%.[1]

Most HVAC systems found in buildings constructed after the 1980s use forced air systems, typically variable-air-volume (VAV) distribution systems [5] in North America. Forced air systems, or all-air systems, are designed to provide an indoor air heat balance to maintain occupant thermal comfort. These all-air systems can respond relatively quickly to changes in zone air temperatures due to the low thermal inertia of the air in the occupied space. Thus, conventional feedback controllers are generally adequate for this type of application.

Radiant heating and cooling systems meet 50% or more of the thermal load in the occupied space through long-wave radiant exchange. Radiant systems offer several advantages over typical all-air HVAC systems, enabling them to reduce HVAC energy consumption while maintaining equal or better occupant thermal comfort [6]. As a result, radiant systems are finding increasing application in high performance buildings [7], with over half of the zero net energy buildings in North America using radiant systems [8]. This current study is focused on hydronic radiant slab cooling systems, also called thermally activated building systems [9]. These systems use tubes embedded in the slab to circulate chilled water through the slab and use relatively large areas, typically the whole floor, ceiling, or both surfaces, for heat exchange, thereby reducing the temperature difference between the chilled water and the occupied space [9]. The advantages are:

- improved heat transport efficiency from the use of water rather than air,

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[1] A meta-study of commissioning identified 16% median actual savings from retro-commissioning [3], and a study of 481 operational issues identified in existing commercial buildings found that control problems accounted for >75% of the causes of energy waste [4].

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- higher chilled water supply temperatures than are used in all-air systems, enabling greater use of water-side free cooling [10], and
- the ability to control the building's thermal mass for energy storage [11,12].

However, radiant slab systems are challenging to control due to their large thermal inertia. The time taken to respond to control signals is typically several hours or more [13], making feedback control of zone temperature infeasible. Any attempt to switchover quickly from heating to cooling or vice versa will result in wasted energy [14] and it is recommended that switchover time should be greater than 24 h [15,16]. The problem, in cooling mode, now becomes managing the heat extraction rate while considering the building's thermal mass within a single day to avoid both under- and over-cooling of the space during occupied hours. Although there is no clear consensus on a common control strategy, current control methods for radiant slab systems typically use heuristic feed-forward control, in which the supply water temperature or flow rate is based on ambient wet-bulb temperature, occupancy schedules or utility tariffs [17–19], or some combination thereof, to maintain a relatively constant slab temperature for all hours of the day. The advantage of this control strategy is that the peak cooling capacity of the plant system can be reduced since the heat extraction rate is spread over 24 h but it may not allow for active control of the thermal storage in the slab. Control of the thermal storage in the slab enables load shifting, in which the load profile of the HVAC system is manipulated for the building stakeholders' benefit. The operation of the HVAC system can be shifted to nighttime hours where favorable weather conditions and electricity prices exist [20]. The ability of the HVAC system to shift load also enables a large fraction of the load of the building to participate in utility demand response programs, which aim to stabilize power grids [21].

The radiant slab research community has been actively developing control strategies, with the aim of exploiting the advantages of radiant slab cooling systems discussed above. A major effort has been undertaken in model predictive control (MPC) [19,22]. Model predictive control (MPC) is an advanced control method that is now attracting increasing interest in the buildings industry [23–25]. MPC can use forecasts of weather [26], occupancy, and energy price signals [27,12,28] to manage thermal energy storage, e.g. in radiant slabs, to improve occupant thermal comfort and reduce energy consumption and costs [12,23]. In MPC, an optimization problem is solved on-line to obtain the current control action [29]. MPC returns a sequence of optimal control actions based on the current state and dynamic model of the plant, system constraints, and minimization of a cost function; only the first control action of the sequence is applied and the procedure is repeated at predetermined intervals. An often cited barrier to its implementation in the building industry is its high computational cost and complexity. In this study, it was shown that with the proper model structure, the model can be identified and is accurate enough to implement real time control and realize energy savings over conventional controllers and the process can be simplified through the use of an open source MPC toolchain.

The main contributions of this experimental study are the demonstration of a MPC model structure for radiant slab cooling systems that can be easily identified, robust, and accurate enough to be used for real-time control and the direct comparison of MPC to heuristic control based on a fixed operational schedule using a matched pair of test cells.

The rest of the paper is organized as follows. Section 2.1 describes the MPC controller used in this study with more detail. Sections 2.2–2.4 describes the test facility, measurement instrumentation, and experimental setup used to carry out this study. Sections 3 and 4 gives the experiment results and concluding remarks, respectively.

2. Methodology

2.1. MPC controller

The MPC controller has the goal of determining a binary control output (ON/OFF) of the radiant slab system that minimizes the weighted combination of comfort violations and energy consumption over a prediction horizon of N time steps. The control problem is defined in Eq. (1) [31].

$$\min_{c_k,h_k} \sum_{k=t}^{t+N} \left[\rho \max\{x_{z,k}-x_{\max,k}, 0, x_{\min,k}-x_{z,k}\} + c_k + h_k\right]$$
$$\text{subject to } x_{k+1} = \begin{cases} A_{cool}x_k + W_{cool}d_k & if\ c_k=1,\ h_k=0 \\ A_{heat}x_k + W_{heat}d_k & if\ c_k=0,\ h_k=1 \\ A_{coast}x_k + W_{coast}d_k & if\ c_k=0,\ h_k=0 \end{cases} \quad \forall k \in \{t,\ldots,t+N-1\} \tag{1}$$

where $x_k = [x_{slab,k} \quad x_{z,k}]'$ and $d_k = [d_{sol,k} \quad d_{oat,k} \quad d_{hg,k}]'$ are the state and disturbance vectors, respectively, $x_{slab,\,k}$ is slab temperature [°C], $x_{z,\,k}$ is zone operative temperature [°C], $d_{sol,\,k}$ is solar irradiance [W/m^2], $d_{oat,\,k}$ is outdoor dry-bulb air temperature [°C], $d_{hg,\,k}$ is the sum of the heat gains from the lights, miscellaneous loads and occupants [W], $x_{\max,\,k}$ and $x_{\min,\,k}$ are the maximum and minimum bounds for the zone operative temperature [°C], c_k and h_k are indicator variables for the cold and hot water valves, respectively, and ρ is the weight to adjust between comfort satisfaction and energy consumption. The subscript t indicates the actual time when the optimization takes place while k indicates the future predictions beyond time t.

The optimization problem in (1) can be equivalently formulated as a mixed-integer linear program; the steps are described briefly below. The reader is referred to Borrelli et al. [32] for a more in-depth discussion of MPC and hybrid system modeling. The temperature violation cost in (1) is formulated as a maximum of three linear pieces. This cost term is transformed into a linear program by means of slack variables. At each time step, a slack variable is introduced and set greater than or equal to the three linear pieces at that time step. The temperature violation cost then becomes the sum of the slack variables. Next, the switched system dynamics can be formulated in simplified form as follows for each time step k.

$$x_{k+1} = z_1 + z_2 + A_{coast}x_k + W_{coast}d_k \tag{2a}$$

$$z_1 = \begin{cases} A_{cool}x_k + W_{cool}d_k - A_{coast}x_k - W_{coast}d_k & if\ c_k = 1 \\ 0 & if\ c_k = 0 \end{cases} \tag{2b}$$

$$z_2 = \begin{cases} A_{heat}x_k + W_{heat}d_k - A_{coast}x_k - W_{coast}d_k & if\ h_k = 1 \\ 0 & if\ h_k = 0 \end{cases} \tag{2c}$$

$$c_k + h_k \le 1 \tag{2d}$$

The remaining switched dynamics are then reformulated as mixed-integer linear constraints as follows.

$$-M_1c_k + z_1 \le A_{cool}x_k + W_{cool}d_k - A_{coast}x_k - W_{coast}d_k \tag{3a}$$

$$m_1c_k - z_1 \le -A_{cool}x_k - W_{cool}d_k + A_{coast}x_k + W_{coast}d_k \tag{3b}$$

$$m_1(1-c_k) + z_1 \le 0 \tag{3c}$$

$$-M_1(1-c_k) - z_1 \le 0 \tag{3d}$$