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Nonlinear model predictive control for a heating and cooling system of a low-energy office building

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ABSTRACT

Model predictive control (MPC) is highly suitable for building heating and cooling control because it exploits disturbance predictions, obeys constraints, and enables optimal building operation in terms of user comfort and energy efficiency. This work presents a highly efficient nonlinear modular MPC concept. It optimally controls both, heating and cooling activities in a low-energy office building simultaneously. Relevant system nonlinearities are considered through a nonlinear prediction model, an LTI MPC optimization step, and an efficient mixed-integer mapping to setpoint temperatures in the building. The involved optimization problems are efficiently solvable and enable realtime control, and the controller structure allows for retrofitting and can directly be incorporated into the existing building control infrastructure. A clear formulation of thermal user comfort and energy efficiency allows straightforward tuning. Excellent control performance and robustness are observed in detailed co-simulation studies, significantly outperforming a classical rule-based reference control law. Possible approaches to analyze robust stability of the controlled system are discussed and related to results of robust TS-fuzzy system analysis.

1. Introduction

1.1. Motivation and overview

The residential and commercial building sectors consume about 40% of the end use of energy world wide. The main part of about 75% accounts to heating, cooling, ventilation and preparation of hot water. Energy savings in the building sector thus contribute significantly to world-wide energy usage reduction. To secure the energy supply, the European Union declared that improving energy efficiency is the best way to guaranteeing energy security. A change of energy end use will thus play a major role in the reduction of greenhouse gases and pollution produced by the combustion of fossil fuels [1,2].

The control task in the present context is to provide satisfactory thermal user comfort at minimum energy consumption by a suitable building controller. A low-energy office building serves as basis for modeling, control design, and co-simulation-based validation.

Model Predictive Control (MPC) for building control has seen strongly increasing research interest in the last years: to tap the full energy-saving potential of actively controlled buildings (or enable active, optimal demand response in interaction with a smart energy grid), it is essential to exploit available predictions of the relevant disturbance effects (such as weather, solar radiation, occupancy, time-varying grid limitations, or dynamic pricing of grid energy). Also, system constraints typically have to be obeyed (e.g. limits on heat flow and temperature variation). These issues are optimally addressed by MPC which employs predictions of the future states of the system over a suitable horizon and optimizes, at each sampling instant, a sequence of control signal values so that a predefined objective is minimized while obeying the considered constraints. First experiments indicate a high energy saving potential for building systems that can be realized by using MPC instead of classical controllers such as Rule-Based Control (RBC) [3].

As outlined in [4], most building MPCs utilize linear time-invariant (LTI) prediction models of the building thermal behaviour. The resulting optimization problems (typically linear or convex

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quadratic programs) are efficiently solvable, and various efforts have been made to extend these controllers' performance, robustness, and applicability. The resulting control input signals are often intermediate quantities (such as heat flows) that still need to be realized in the building services control system, for example via hierarchic or cascaded control schemes [5]. However, modern low-energy buildings often rely on energy supply services involving switched aggregates (e.g. heat pumps) or on/off-valves to distribute a centrally supplied feed flow to numerous building zones. Considering these nonlinearities correctly in optimization-based control allows to tap the full energy-saving potential of such building systems. The resulting hybrid system dynamics usually require high effort to solve optimal control problems; directly considering these effects via MPC typically generates mixed-integer optimization problems which quickly become untractable for real-time optimization when model complexity increases.

These aspects clearly show the need for an efficient MPC concept that addresses the relevant nonlinearities and fulfills realtime and retrofitting requirements. The modular MPC concept proposed in this work will be designed to fulfill these requirements.

1.2. Building model and nonlinearities

To model the building dynamics for MPC, a balanced complexity trade-off has to be found: the model has to be simple enough to be solved in an adequate amount of time but complex enough to reproduce the dynamics of the real building with sufficient accuracy. The modeling strategy is important, since obtaining the building model can be a time-demanding process, and it is crucial for the success of MPC [4]. A detailed discussion on advantages and disadvantages of different modeling strategies is given in [6]. To model the thermal building and building services behaviour, a common classification of the model type is

- black-box modeling as in [7–10],
- grey-box modeling with parameter identification as in [3,11–13], or
- white-box modeling as in [14,15].

Since for most new buildings extensive plan data are at hand, a white box modeling approach is chosen here. The model offers physical insight and reduces the need for on-site identification procedures. Difficulties of the identification process related to the persistent excitation property and the closed-loop nature of the model can be avoided [6,12].

Special care in modeling is required to adequately address the nonlinear and switching behavior of the building and the heating, ventilation and air conditioning (HVAC) system. Building models with nonlinear elements have been utilized in existing works: in [15], the state-space model is bilinear, taking into account the reduction of the solar radiation by pitching of window blinds. A static nonlinearity is compensated in [13] between the heat flux of the radiators and the temperature difference between inlet water temperature and zone temperature. Smooth nonlinear complex systems comprised of a set of local linear models are identified in [10]. A nonlinear model is the basis of the MPC in [14] where a chilling system is presented. However, the approach presented in the present work using a white-box nonlinear model is a novel idea.

Nonlinearities concerning switching parts of the building can be addressed in the MPC algorithm. These hybrid systems [16] are formulated for buildings in [14]. Nonlinear cost functions are formulated for example in [11,17].

1.3. Model predictive control in buildings

Building MPC has received considerable and sharply increasing research interest in the last years, see [18,4]. The authors of [18] discuss the trade-off between energy consumption and room comfort for occupants. In fact, MPC has two possibilities to improve the performance of buildings compared to RBC: Load shifting or active storage of energy, and optimizing the efficiency of the component mechanisms. Load control of the building mass is presented already in [19]. In that study the author points out that the saving potential is sensitive to weather conditions and occupancy schedules. The importance of occupancy information for MPC is presented more profoundly in [20].

The use of prediction data for MPC is crucial, but it is subject to uncertainties as mentioned in [18,4]. The uncertainty of predicted data (weather and internal gains) causes violations of the comfort criteria. This problem is taken into account in [21,22] by two concepts: Stochastic MPC and Randomized MPC, resulting in a robust controller for uncertain weather and internal gain predictions.

Several simulation studies concerning building MPC are performed e.g. in [17,22,23]. The authors in [12,13,24] perform simulation studies for intermediate heated buildings, defined by a change of the room reference temperature during off-hours. This is also considered here for the office building controlled in this paper.

Recent experimental results show the potential of MPC in buildings: An online full-scale implementation of an MPC for an HVAC system is presented in [11]. The results of the MPC are delivered as set points to the controllers of the lower control level. The energy consumption is reduced by up to 60% compared to RBC. In [14] an HVAC MPC for a chilling system is presented. The controller improved the coefficient of power (COP) by 19.1% when being implemented at the University of California, Merced campus, USA. Experiments using thermally activated building systems are presented in [3,7]. While in [7] only predictions of the outside temperatures are utilized, Ref. [3] performs the experiments with weather and occupancy predictions. In both articles the MPC is compared to RBC or similar control strategies. The authors state an energy saving potential of about 20%.

Most of the MPC consider either heating or cooling systems, those being capable to optimize both heating and cooling of a building ventilation system simultaneously can be found in [9,11,23]. Only the publications concerning the OptiControl project report simulations of cooling and heating thermally activated building systems (TABS), see [15,21,22].

1.4. Proposed modular MPC concept for building control

This paper presents a novel model predictive controller scheme for the heating and cooling system of a low-energy building using prediction data for weather and internal gains (occupancy, lights). A modular Model Predictive Control (MMPC) concept is devised that fulfills the following requirements: realtime capability, detailed modeling (16 states corresponding to 16 zone temperatures) of a nonlinear hybrid dynamic building system, and direct integrability into the existing building control system by providing TABS temperature setpoint trajectories. The MMPC exploits an available nonlinear prediction model, adjusts the temperatures and heat flows of the building system to optimize energy efficiency and thermal comfort based on a linear thermal model, and maps the resulting heat flows optimally to TABS setpoint trajectories via a reduced-complexity mixed-integer optimization step. This way, high control performance and robustness are obtained, computational effort is kept small so as to enable real-time control, and the concept is well-suited for retrofitting of existing building control systems.