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Offset-free model predictive control for an energy efficient tropical island hotel

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ABSTRACT

This paper presents the application of an offset-free model predictive controller (OF-MPC) for an energy efficient operation of the central chiller plant in a case study hotel on a tropical island. The OF-MPC performance is simulated under the mismatch between the real system's dynamics and the controller's internal model, the incidence of stochastic unmeasured disturbances, and different weather conditions and building occupancies over weekly periods throughout seven months. This controller is compared with two frequently used open-loop control methods (i.e., Baseline and Conventional). The simulations suggested that the proposed OF-MPC is able to track the set-point temperature of the worst-case reference room with lower thermal comfort violations than the Conventional. Furthermore, there is a significant energy savings potential for the OF-MPC compared to both strategies, which is deteriorated under extreme weather conditions. The promising OF-MPC ensures that the cooling capacity delivered by the central chiller plant can match the actual building cooling load, making the chilling system operate energy efficiently.

1. Introduction

Tourism plays an important role in the economical development of tropical islands in the Caribbean Sea. In Cuba, it is an industry that generates over 3 million arrivals per year and one of the main sources of revenue for the island. This sector, with steady annual growth, has had a reasonable tendency to increase the number of hotels and rooms. Raising the quality of service, reducing costs and preserving the environment are continuous challenges in this area.

Buildings located in the tropical region are generally influenced by high values of ambient temperature and solar radiation throughout the year. Heating, ventilation and air-conditioning (HVAC) systems (e.g., air conditioners, fan coil units, air-handling units, etc.) are installed to cool down facilities maintaining the occupants' comfort required for indoor areas. In tropical islands, it is a usual practice to exploit central chiller plants for cooling down large buildings, where chilled water is circulated through a series of terminal fluid-to-air heat exchangers, i.e., fan coil units (FCU), to provide cooling energy to the thermal zones. The operation of chillers leads to a huge electricity consumption and a peak demand. In Cuban hotels, air-conditioning is the most power demanding system and can account for about 65% of total electricity consumption. However, there are opportunities to reduce energy consumption and costs without affecting the level and quality of services through an effective energy management.

Energy performance of complex chilled water systems under various working conditions has been treated in the literature [1–4]. In Ref. [1], the strategy optimizes control settings such as: the chilled water supply temperature set-point, the operating number of pumps distributing water to terminal units, the operating number of heat exchangers, the optimal pressure differential set-points and the number of chillers operating in delimited zones. The performance of this scheme reported electric energy savings around 1.28–2.63% of the total in the system under investigation as compared to the strategy using the fixed temperature and pressure differential set-points. A similar approach was followed in Ref. [2], but the optimal strategy was formulated using simplified

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Nomenclature

T	temperature (°C)
I	intensity of solar radiation (W/m^2)
Occ	occupancy (–)
t	time instant (s)
f	state equation
g	output equation

Subscripts

room	reference thermal zone
extra	additional state
w	water
s	supply
r	return
amb	ambient
global	global
m	measured
um	unmeasured
sp	set-point
t	target

linear self-tuning models of major components, and a genetic algorithm (GA) was used to solve the optimization problem and search for globally optimal control settings. The results showed that this strategy can save about 0.73–2.55% daily energy of the system studied, as compared to a reference strategy using conventional settings. Wang et al. [3] presented an adaptive optimal control strategy for online control of complex chilled water systems involving intermediate heat exchangers to enhance operation and energy performances. This strategy determines the optimal settings which minimize the energy consumption of chilled water pumps. The results of the energy performance evaluation tests showed that 5.26–14.69% of the pump energy could be saved when using the proposed optimal control strategy in normal operation as compared to conventional strategies. A method to enhance the robustness and reliability of the model-based optimal control strategies is reported in Ref. [4]. The method adopts the fuzzy *c*-means clustering method and the fuzzy inference system to predict the errors in model outputs. The simulation test results showed that the enhanced robust control strategy can offer more significant energy savings (up to 3.22%) compared to the conventional model-based optimal control strategy. A simulated virtual platform representing a chilled water system in a super high-rise building was established to validate and evaluate the above strategies.

Model predictive control (MPC) is a modern control technique that has had a phenomenal success in the process industries mainly due to its conceptual simplicity and its ability to handle easily and effectively complex systems with hard control constraints and many inputs and outputs [5]. MPC is a form of control in which the current control action is obtained by solving on-line, at each sampling instant, a finite horizon open-loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant [6]. When using MPC to drive the controlled outputs of the plant to their desired targets at steady state (e.g., when tracking constant references without offset under plant-model mismatch), this controller is referred to as offset-free MPC (OF-MPC) [7–10]. Generally, a building MPC aims to find at every control iteration the control input trajectory over a given prediction horizon that minimizes total operating costs while satisfying comfort constraints [11].

The MPC application of thermal energy storage in building cooling systems has been reported by Ma et al. in Refs. [12–14]. These works deal with buildings at university campus, equipped with a water tank used for actively storing cold water produced by a series of chillers. An MPC for the chillers operation is designed in order to optimally store the thermal energy in the tank by using predictive knowledge of building loads and weather conditions. The proposed MPC optimized the scheduling and operation of the central plant to achieve lower electricity cost and better efficiency.

Further experimental research on buildings that have been controlled by MPC, using diverse HVAC actuators, different lapses of test time and MPC models, were summarized by Sturzenegger et al. in Ref. [11]. This paper reports the final results of the predictive building control project OptiControl-II[1] that encompassed seven months of MPC of a fully-occupied Swiss office building. In addition, a cost-benefit analysis of building MPC for cases similar to the investigated target building was discussed.

Furthermore, the design and implementation of different classes of MPC in systems with uncertainties, i.e., plant-model mismatch, measurement noise, and/or unmodeled disturbances, have been treated in the literature [15–18]. A robust model predictive control strategy for improving the supply air temperature control of air-handling units is presented in Ref. [15]. The uncertainties of the time-delay and system gain were formulated using an uncertainty polytope. Based on this formulation, an off-line LMI-based robust model predictive control algorithm is employed to design a robust controller which can guarantee a good robustness subject to uncertainties and constraints [19]. The proposed robust strategy was evaluated in a dynamic simulation environment of a variable air volume air-conditioning system in various operation conditions by comparing it with a conventional PI control strategy. Ref. [16] describes the application of an OF-MPC to a vapor compression cycle (VCC) interfaced with a building model implemented in EnergyPlus. The superior closed-loop performance of the OF-MPC strategy is demonstrated for a VCC model in isolation, subject to realistic disturbances and measurement noise. Maasoumy et al. [17] proposed a modeling framework for on-line estimation of states and unknown parameters leading to a parameter-adaptive building model. A nominal MPC, a robust model predictive control (RMPC), and a common building rule based control (RBC) were formulated and their performances were compared for various model uncertainty levels. A methodology to select the best controller among the ones studied was presented which leads to optimum trade-off between energy consumption and comfort level. Huang et al. [18] presented a hybrid model predictive control (HMPC) scheme based on neural network feedback linearisation for a commercial building. The control model for the HMPC is developed using a simplified physical model, while the uncertainties associated with HVAC process (i.e., air-handling units) are handled independently by an inverse neural network model. This approach was tested through both, simulations and a field experiment, and considerable savings without violating thermal comfort were achieved.

From the aforementioned review, it has been demonstrated that MPC for building HVAC systems outperforms other control techniques. MPC generally provides superior performance in terms of: energy consumption, cost savings, efficiency and coefficient of performance (COP), peak load shifting capability, transient response, robustness to disturbances and changes in operating conditions, as well as thermal comfort enhancement [20].

This paper presents a novel application of an OF-MPC for an energy efficient operation of the central chiller plant in a case

[1] www.opticontrol.ethz.ch.