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Occupancy behavior based model predictive control for building indoor climate—A critical review

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ABSTRACT

This paper reviews occupancy based model predictive control (MPC) for building indoor climate control. Occupancy behavior in buildings is stochastic and complex in nature. With better understanding of occupancy presence in rooms and spaces, advanced controls, such as MPC, can be designed to achieve a more energy efficient operation, compared to more traditional control methods, while comfort is maintained. This paper starts with an overview of traditional controls implemented in buildings, and importance of occupancy based controls. Various control-oriented building modeling methods including physics-based and data-driven models are reviewed. Later on, a comprehensive review of MPC in terms of control theory, objective functions, constrains, optimization methods, system characteristics and various types of MPC is presented conducted. In principle, MPC finds an optimal sequence of control commands to optimize an objective function, considering system model, disturbances, predictions and actuation constraints. Lastly, occupancy based controls including commonly used rule-based and latest model-based controls are reviewed. In addition, a few experimental studies are presented and discussed. The paper presents a holistic overview of occupancy-based MPC for building heating, ventilation, and air conditioning (HVAC) systems, and discusses current status and future challenges. The purpose of this paper is to provide a guideline forresearchers who would like to conduct similar studies to have a better understanding of established research methods.

Contents

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1. Introduction

1.1. Overview

Buildings are responsible for almost 40% of the whole energy use in the United States [1]. Reducing energy use in buildings is an important factor in dealing with CO_2 emission and global warming due to the fact that, buildings energy use stands for one-third of greenhouse gas emissions [2]. Additionally, buildings do not maintain a constant energy use during the day. 20% of the electricity production capacity is built only to meet the peak demand which is used only 5% of the time [3,4]. One of the biggest consumers of energy in buildings is air conditioning unit. About 40% of building energy is being used by HVAC system in commercial buildings. There are many research studies trying to reduce energy use in this section. There are many studies showing that up to 30% energy saving is achievable, switching from traditional methods of control to more efficient control methods. Most of the control methods used for HVAC are feedback controllers, such as proportional–integral–derivative (PID), and Bang–Bang controller. These controllers have been designed to maintain comfort rather than taking efficient control action. This makes the optimal control of this component crucial.

Model predictive controller (MPC) is a method to design sequences of control inputs to optimize an objective function considering defined and forced constraints. This controller uses the model of the system, system inputs, anddisturbances (e.g. outdoor weather, occupancy, solar gain, etc) to predict future states (e.g. indoor temperature) in order to make the most efficient control action [5,6]. This controller is suitable for controlling the HVAC system using weather and occupancy predictions and information available on energy peak price [3,4]. MPC can utilize building mass as a thermal energy storage or cold storage facilities for load shifting to off-peak hours [7–10]. MPC can be used to manage energy use from different available sources of energy in micro-grids and buildings [11,12]. MPC can be used to manage free sources of energy such as solar radiation through controlling window blinds [13]. MPC can result in about 27% energy saving for the air handler unit in a multi-zone building [14]. MPC can be used in HVAC energy management for interconnected water and air side to find an optimum controller for different situations [15]. MPC can use occupancy predictions or schedule to minimize energy use while maintaining comfort. Most of research papers show that using MPC to control HVAC system or room temperature can save ten to fifty present energy depending on controller configuration, and disturbances predictions [14,16–23]. There is a simulation report from Pacific Northwest National Laboratory (PNNL) on occupancy based Variable Air Volume (VAV) box control in 4.4 billion ft^2 commercial buildings (6% of total commercial floor space) in different climate zones showing an energy saving opportunity up to 23% by controlling VAV air flow based on room occupancy sensors [24].

1.2. Traditional control methods for HVAC system

The nonlinear and complex dynamic characteristic of HVAC system has made control a challenge. This challenge becomes even more difficult considering uncertain and time-varying environment and disturbances. In addition, building operators are interested in having an optimal controller to minimize cost in their system, which will add some other important factors to the problem, such as: optimal control methods, system modeling, etc.

Building automation system (BAS) provides a centralized management system to control heating, ventilating, air conditioning, lighting, safety and security to achieve occupant comfort and efficient building operation [25]. Most of control methods used in BAS can be divided into two main categories: supervisory and local controllers. Supervisory (High-level) controller tries to define set points for local controllers to achieve cost-efficient thermal comfort without violating system constraints [26]. Local (low-level) controllers, control each component of the system and bring functionality to the system. This category can be divided into two subcategories: sequencing and process control. Sequencing control turns each component on and off, while process-controller, brings each component states to desired values [27]. Building climate control can be as simple as a thermostat in a small residential building or as complex as a network of sensors and VAV boxes in a commercial building.

Different control methods can be used for building climate control. In [28] Optimal, MPC, PID, Robust, Nonlinear and adaptive controllers are reviewed as hard controllers. Optimal and model predictive control methods are known for their attractive capability of energy saving. Between these two, MPC can deal with model uncertainties and disturbances. Also, robust controllers are known for their capability in dealing with model uncertainties and disturbances [29]. There are a few papers studying nonlinear and adaptive controllers which can deal with system nonlinearity and adapt to small changes in the system respectively. Among all these controllers, PID, step and Bang–Bang controllers are more popular, due to their simplicity and ease of implementation. However, the on-off controller shows a big swing from the set point, and PID controller parameters tuning is a challenge in time-varying environments [30].

Model predictive controller is not a new control method. However, due to high computational cost of this method, it has not been attractive to researchers for building control in the past. To the best of the author's knowledge, there are many early studies trying to design optimal controller for HVAC system [31–33]. The idea of using optimization techniques to reduce energy use can be tracked back to 1970's [34]. MacArthur et al. [35,36] used receding horizon and model predictive control to minimize energy use in buildings in 1993. In 1999 Wang used TRNSYS to simulate building and HVAC system to test his optimal supervisory controller[37]. To the best of the author's knowledge it has been less than ten years that, this controller has received the attention of researchers in buildings' climate control.