Journal of Process Control xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Decentralized predictive thermal control for buildings

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ARTICLE INFO

Article history:
Received 28 March 2013
Received in revised form 16 October 2013
Accepted 17 February 2014
Available online xxx

Keywords:
Building thermal control
Decentralized control
Model predictive control
Extended state observer

ABSTRACT

This paper studies the problem of decentralized control design for thermal control in buildings, to achieve a satisfactory trade-off between underlying performance and robustness objectives. An output-feedback, model predictive framework is used for decentralized control which is based on a reduced order system representation. It entails the use of decentralized extended state observers to address the issue of unavailability of all states and disturbances. The decision on control architecture selection is based on an agglomerative clustering methodology developed previously [22]. The potential use of the proposed control design methodology is demonstrated in simulation on a multi-zone building, which quantifies the tradeoffs in performance and robustness with respect to the degree of decentralization.

1. Introduction

The building sector accounts for more than 40% of the total energy consumption in the United States [1]. More than one-third of the energy consumption in a typical building results from heating, ventilation and air-conditioning (HVAC) systems [2,3]. Therefore, improvements in the energy efficiency of building thermal management have the potential for a large economic and environmental impact. Hence, efficient thermal control of buildings has received considerable attention in the literature [4–9].

From a controls perspective, a building is a complex MIMO system with dynamically interconnected zones and walls. The key control objective in the thermal management of buildings is to satisfy occupant thermal comfort requirements with minimal energy consumption. Unlike many other complex MIMO plants, buildings have some unique qualities that make control challenging and choice of controller architecture important. Most buildings in the United States have a life-span of 75–100 years [10], and it is estimated that 85% of all buildings that would exist in 2030 exist today [11]. Given the large number of actuators and sensors used in modern commercial buildings, they are *de facto* susceptible to actuator and sensor faults during their lifetime [12]. In this work, we propose a methodology to design control systems for buildings that are tolerant of high probability failure events.

In theory, a centralized controller, consisting of a single control agent receiving building-wide sensory data and using complete information of the system dynamics, has the potential to control the building optimally. However, it is sensitive to sensor and communication network failures [13,14]. A decentralized control architecture may be more resilient to such failures because of its ability to contain their effect locally [15]. However, decentralization may result in suboptimal performance (evaluated with respect to occupant comfort and energy consumption) when compared to a centralized controller, because it disregards any coupling from other subsystems while making control decisions for a given subsystem. Therefore, there exists a fundamental trade-off between optimality and robustness (defined here as resilience to failures) with regard to the degree of decentralization [16].

Decentralization in the context of building thermal control has been studied previously [17–21]. The most common architecture is a multi-agent scheme where each control agent is matched to a single zone in the building. This results in the smallest possible subsystem size, which is beneficial from a robustness point of view. What is desired is a systematic decentralization procedure that can quantify the specific trade-offs under consideration that exist in a control design context. Appropriate control algorithms such as proportional-integral-derivative (PID) control, linear quadratic regulation (LQR) or model predictive control (MPC) can then be used to design controllers for the decentralized architecture obtained. Previously [22] developed a methodology to determine appropriate decentralized control architectures, which provide a satisfactory trade-off between performance and robustness objectives in the context of building thermal

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http://dx.doi.org/10.1016/j.jprocont.2014.02.015
0959-1524/

Nomenclature

N_w	number of walls surfaces in the building
N_z	number of zones in the building
N_{zi}	number of zones in ith cluster
S_z	set of all zones in the building
S_{zi}	set of zones in ith cluster
$\mathbf{T_w}$	vector of wall surface temperatures
$\mathbf{T_w^i}$	vector of wall surface temperatures in ith cluster
$T^i_{w,k}$	temperature of kth wall surface in ith cluster
$\mathbf{T_z}$	vector of zone temperatures
$\mathbf{T_{z,ref}}$	vector of zone temperature set-points
$\mathbf{T_z^i}$	vector of zone temperatures in ith cluster
$\hat{\mathbf{T}}_\mathbf{z}^\mathbf{i}$	vector of zone temperatures estimates (guesses) in ith cluster
$\mathbf{T^i_{z,ref}}$	vector of zone temperature set-points in ith cluster
$\mathbf{T^i_{z,meas}}$	vector of zone temperature measurements in ith cluster
$T_{z,i}$	temperature of ith zone
$T_{z,i,\mathrm{ref}}$	set-point temperature for ith zone
T_a	ambient temperature
T_g	temperature of ground below building
$T^i_{z,n}$	temperature of nth zone in ith cluster
T_{supp}	temperature of supply air provided by VAV system
$\mathbf{d_w}$	vector of unknown thermal loads acting on wall surfaces
$\mathbf{d_z}$	vector of unknown thermal loads acting on zones
$\mathbf{d_w^i}$	vector of unknown thermal loads acting on wall surfaces in i^{th} cluster
$\mathbf{d_z^i}$	vector of unknown thermal loads acting on zones in ith cluster
$\bar{\mathbf{d}}_\mathbf{w}^\mathbf{i}$	vector of aggregated thermal loads acting on wall surfaces in reduced order model for ith cluster
$\bar{\mathbf{d}}_\mathbf{w}^\mathbf{i}$	vector of aggregated thermal loads acting on zones in reduced order model for ith cluster
$C^i_{w,k}$	thermal capacitance associated with kth wall surface in ith cluster
$C^i_{z,n}$	thermal capacitance associated with nth zone in ith cluster
c_{pa}	specific heat capacity of air
$x(k+l\|k)$	projected value of quantity x after l time steps in future, given $x(k)$. Note $x(k\|k)=x(k)$.
$\mathbf{u}$	vector of control inputs
$\mathbf{u^i}$	vector of control inputs in ith cluster
u^i_n	control input for nth zone in ith cluster
$0_{m,n}$	zero matrix of dimension $m \times n$
$\dot{m}^i_{\max,n}$	maximum air mass flow rate available for nth zone in ith cluster
$Q^i_{RH-\max,n}$	maximum reheat power rate available for nth zone in ith cluster

control. Suitable optimality and robustness metrics were introduced and an agglomerative clustering procedure was adopted to partition any building into clusters with tractable computational complexity for decentralized control. In [22], the design of decentralized controllers based on the determined control architectures was not considered. This paper seeks to address this requirement by focusing on the design aspects of decentralized control for a given control architecture.

A key issue in control design for thermal control of buildings is the unavailability of accurate and reliable information about certain aspects relevant to the thermal dynamics. In particular, thermostats installed in buildings measure only the zone air temperatures which are associated with the thermal comfort of occupants. Therefore, temperatures of walls which also participate in the building's thermal dynamics are usually not known. Additionally, thermal loads from factors such occupants, lighting, appliances and radiation are difficult to quantify and predict accurately, resulting in potentially large uncertainties in the description of thermal dynamics inside a building.

We observe that existing literature in the area of building thermal control seek to address these issues for a particular building by (a) using data-driven or parameter identification type of modeling approaches [23], (b) describing the dynamics only in terms of zone temperature states [6], and (c) adding additional sensors for prediction of unknown states or thermal loads [24,25]. Complementing previous results, in this paper we explore control design methodologies which can be applied to a general class of buildings without the need to add additional sensors or develop time-consuming and resource-intensive high-fidelity models. We also seek to address other challenges associated with building control design such as the potentially large dimension of the state-space for the underlying thermal dynamics [26] and the presence of constraints originating from practical considerations. The above concerns are addressed by first developing reduced order model representations for the thermal dynamics and then using decentralized extended state observers to simultaneously estimate the unknown states and disturbances. This is followed by control design based on the MPC framework. Lastly, a simulated test environment is developed and employed to investigate the usefulness of the tools proposed in this paper.

The proposed sequence of steps leading to control design is outlined in Fig. 1. In this work, although we make specific choices for implementing each of these steps, Fig. 1 should be interpreted as a general guideline where each step can be implemented using one of several available tools. For example, we use MPC for control design in step 6 as it has been extensively applied in the building systems control

Please cite this article in press as: V. Chandan, A.G. Alleyne, Decentralized predictive thermal control for buildings, J. Process Control (2014), http://dx.doi.org/10.1016/j.jprocont.2014.02.015