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A robust model predictive control strategy for improving the control performance of air-conditioning systems

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ABSTRACT

This paper presents a robust model predictive control strategy for improving the supply air temperature control of air-handling units by dealing with the associated uncertainties and constraints directly. This strategy uses a first-order plus time-delay model with uncertain time-delay and system gain to describe air-conditioning process of an air-handling unit usually operating at various weather conditions. The uncertainties of the time-delay and system gain, which imply the nonlinearities and the variable dynamic characteristics, are formulated using an uncertainty polytope. Based on this uncertainty formulation, an offline LMI-based robust model predictive control algorithm is employed to design a robust controller for air-handling units which can guarantee a good robustness subject to uncertainties and constraints. The proposed robust strategy is evaluated in a dynamic simulation environment of a variable air volume air-conditioning system in various operation conditions by comparing with a conventional PI control strategy. The robustness analysis of both strategies under different weather conditions is also presented.

1. Introduction

Air-conditioning systems are widely used in commercial and office buildings to provide safe and comfortable environment for building occupants. To maintain a safe and comfortable environment, the basic issue among controls is to maintain the system output at its set points although many studies presented different control strategies to reset control set points or change operation modes for improving system energy efficiency [1–4]. The control of air-conditioning processes is difficult to achieve due mainly to the associated uncertainties, nonlinearities and constraints. The sources of uncertainties may be attributed to measurements and the model structure used for control purpose [5,6]. Nonlinear behaviors happen due to hysteresis in actuators/valves and variations in fluid flow rate and the heat transfer coefficients. In addition, the system has time-varying dynamics and persistent time-varying disturbances, i.e., inlet air flow rate, temperature and humidity due to ever-changing cooling loads and weather conditions. Constraints exist because of the use of actuators, which usually operate with a rate limit and a range limit.

Due to the complexity of air-conditioning systems, there are a number of approaches proposed for the local control of the supply air temperature. They can be roughly categorized into proportional-integral and/or derivative (PI or PID) control [7,8], artificial intelligence control [6,9,10], and robust control [11,12].

PI or PID feedback control algorithm is widely used in HVAC (heating, ventilation and air conditioning) fields due to its simplicity. Usually, the air-conditioning process is assumed to be a first-order plus time-delay system [11,13], and site tests are conducted to determine the process parameters including process gain, time constant and delay time. These parameters are then used to compute the PID control parameters for practical control using Ziegler and Nichols settings or some other settings [14]. However, the control parameters at the testing point may result in aggressive or sluggish response at other work conditions due to that the control parameters cannot cover all the working range of the air-conditioning systems [15].

Artificial intelligence is a newly developing technology, such as neural network control and fuzzy logic control, to deal with nonlinearities or uncertainties in HVAC processes [6,9,10]. Artificial neural network (ANN) has strong modeling capability for nonlinearities; while fuzzy logic control can deal with uncertainties in a straightforward manner. Both methods can find their application in HVAC systems. However, both ANN-based control and fuzzy control require a large amount of system operation data for model training, which should cover the whole process operating range. The collection of such complete data is not easy. Besides, they cannot take account constraints directly in the control design. Therefore, the application of such intelligent methods might be limited in practice.

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Nomenclature

AIAE	average of integrated absolute value of the supply air temperature error (°C)
A, B	matrix coefficients of state-space model
a, b	coefficients of the discrete model
D	control input range constraint
DCV	demand-controlled ventilation
d	integer time delay
e	tracking error (°C)
e^m	largest possible tracking error (°C)
$\boldsymbol{F}$	gain of the state feedback rule
f	cost function
h	sampling interval (s)
K	process gain or system gain (°C^{-1})
N	prediction horizon or number of process sampling
N_p	number of the nested subspaces
$\boldsymbol{Q}$	weight matrix used in the cost function
R	weight factor used in the cost function
$\boldsymbol{S}$	matrix to denote state subspace
T	time constant (s)
u	control input (–)
$\dot{u}$	control input varying rate
$\boldsymbol{x}$	state vector
y	outlet supply air temperature (°C)
Greek symbols	
λ	variable
γ	variable indicating the upper bound of the cost function
δ	constant
Ω_{AB}	polytope
τ	delay time (s)
Subscripts	
act	actual measurement
k	current time instant
r	indicate temperature set point
L	lower bound
U	upper bound

Robust H_∞ control has also been found in the temperature control of air-handling units to deal with dynamic uncertainties [11,12]. Time-delay and process gain uncertainties have been taken into account in the robust control design since they are the major factors affecting the control performance. In robust H_∞ control, the time-delay and the process gain are assumed to lie in an uncertainty set. Pade approximation is used to describe the time-delay. Difficulty with the robust control design may be the selection of the control parameters, including model uncertainty weights and optimization criteria weights, which is the major part of the controller design. Although robust H_∞ control can deal with uncertainties directly, it cannot deal with the associated constraints in the HVAC processes as well, which probably influence the robustness and stability of the controlled system.

This paper presents a robust model predictive control strategy for HVAC processes which can deal with the associated uncertainties (dynamics variations) and constraints in a straightforward manner. When constraints in the process are likely concerned, model-based predictive control (MPC) is a good choice for control design. The development of MPC is considered as the recent major achievement in control literature, which has been widely accepted as the next generation of a practical control technology [16]. The application of MPC in HVAC systems can be found in the Ref. [17], which dealt with constraints but not uncertainties. Therefore, robust MPC is developed for HVAC applications in order to enhance the closed-loop robustness and stability.

In this proposed strategy, the dynamics is represented using a first-order plus time-delay model, of which the time delay and the process gain are assumed to vary in a known range as in the Ref. [11]. An uncertainty polytope is developed to formulate the time-delay and process gain uncertainties, which can bridge the gap between robust model predictive control and its application in air-conditioning systems. An offline model predictive control algorithm developed by Wan and Kothare [18] is employed in this study. It will be shown that the proposed strategy can guarantee a good robustness when uncertainties and constrains are present and can be easily implemented without much user intervention. A typical Variable-Air-Volume (VAV) air-conditioning system for the application of this strategy is presented and the main control problems are identified in Section 2. The robust strategy is described in details in Section 3. In Section 4, the control performance of this robust strategy is demonstrated by comparing with that of a conventional PI control strategy. The robustness analysis is also presented in this section. Conclusions are given in Section 5.

2. Description of an air-conditioning system

The diagram of a typical AHU VAV air-conditioning system and its control instrumentations is shown in Fig. 1. The fresh air is mixed with the air through the recycled air damper, depending on the fresh air damper position (the fresh air damper, recycled air damper and exhaust air damper are interlocked as usual). The AHU controller generates control signals for manipulating the heating coil valve (or cooling coil valve) and the fresh air damper to control the supply air temperature at its set point if the outdoor air is favorable for free cooling. The AHU controller also generates the control signal to the fresh air damper for controlling the fresh airflow at its set point reset by the demand-controlled ventilation (DCV) strategy maintaining acceptable indoor air quality in the heating mode or the mechanical cooling mode. The conditioned air is distributed to the occupied zones via the supply air ducts and VAV terminals. The pressure controller maintains the supply air static pressure at its set point by modulating the fan pitch angle or the frequency of the supply fan. The return air fan is controlled by a controller to maintain the flow rate difference to maintain a positive pressure in the conditioned area.

Usually, an air-handling unit needs to provide heating, free cooling and mechanical cooling at different seasons due to the ever-changing weather conditions in many regions such as Hong Kong. The actual outlet temperature of the AHU is used for the temperature control modulating the heating coil valve, the fresh air damper and/or the cooling coil valve. Fig. 2 presents the conventionally used split-range sequencing control logic [19]. In each of the heating and cooling modes, the air-handling unit usually experiences a wide range of weather conditions and a large change of the internal heat gain of the conditioned area. These external weather disturbances seriously affect the dynamic characteristics (process gain, time constant and time delay) of the air-handling unit together with the ever-varying internal disturbances. In this study, only the temperature control associated with the mechanical cooling processes (i.e., in the partial free cooling mode and in the mechanical cooling mode) is concerned. However, the proposed method can be extended to the control of other processes