Building and Environment 44 (2009) 1850–1863

Contents lists available at ScienceDirect

Building and Environment

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

Predictive control techniques for energy and indoor environmental quality management in buildings

D. Kolokotsa [a,*], A. Pouliezos [b], G. Stavrakakis [c], C. Lazos [c]

[a] Technological Educational Institute of Crete, Department of Natural Resources and Environment, 3, Romanou str., 73133, Hania, Crete, Greece
[b] Technical University of Crete, Department of Production Engineering and Management, University Campus, Kounoupidiana, 73100 Hania, Greece
[c] Technical University of Crete, Department of Electronics and Computer Engineering, University Campus, Kounoupidiana, 73100 Hania, Greece

A R T I C L E I N F O

Article history:
Received 20 October 2008
Received in revised form
12 December 2008
Accepted 15 December 2008

Keywords:
Energy management systems
Predictive control
Bilinear model
Indoor environmental quality

A B S T R A C T

The aim of the present paper is to present a model-based predictive controller, combined with a Building Energy Management System (BEMS). The overall system predicts the indoor environmental conditions of a specific building and selects the most appropriate actions so as to reach the set points and contribute to the indoor environmental quality by minimizing energy costs. The controller is tested using a BEMS installation in Hania, Crete, Greece.

1. Introduction

During the last decades the contribution of Building Energy Management Systems (BEMS) to energy efficiency, improvement of the indoor comfort and environmental quality during a building's operational phase is well recognized. Advanced control techniques based on artificial intelligence (neural networks, fuzzy logic, genetic algorithms, etc.) and distributed control networks offer numerous benefits towards that direction [1–5].

Building energy management and online control systems are reactive to the climatic conditions, building operation and occupancy interventions. Predictive control in conjunction with BEMS on the other hand uses a model to estimate and predict the optimum control strategy to be implemented [6]. While the online control systems can react only to the actual building conditions [7], a model-based predictive control can move forward in time to predict the buildings' reaction to alternative control schemes. Therefore different control scenarios can be evaluated based on suitable objective functions, and create a control state space that corresponds to a building's performance space [8].

A model can be either a "black box" or a "physical" model. In the "black box" or non-physical model approaches, self-learning algorithms, reinforced learning [9] or neural networks [10] are some of the methodologies found in the literature. The benefits of the mentioned approaches are low computational time and the fact that they do not require any specific building modeling expertise, while their limitations are (i) the fact that neural networks require reliable training data that may not be available and (ii) self-learning algorithms cannot move beyond the limits of their experience. When physical models are utilized, the expert has the opportunity to understand the cause-and-effect relationship between the various building components, the control strategies and the climatic conditions. The physical models approach can use stochastic mathematical models [11] or simulation-assisted predictive control [12]. Some physical models though require high computational skills and effort.

In the present work a bilinear model-based predictive control is utilized in conjunction with BEMS, so as to achieve optimum indoor environmental conditions while minimizing energy costs. The bilinear modeling procedure is selected as it is the simplest extension of linear modeling and offers simplicity in the prediction algorithms' calculation procedure. The paper is organized in six sections. Section 2 includes a short description of a building and the installed BEMS. Section 3 incorporates the bilinear model analysis and the identification procedure. Section 4 analyses the predictive control strategy, while Section 5 presents shortly the graphical environment of the predictive control scheme. The experimental analysis including comparison between real and simulated measurements and discussion is presented in Section 6. Finally,

* Corresponding author. Tel.: +30 28210 23017, +30 28210 37209; fax: +30 28210 23003.
E-mail address: kolokotsa@chania.teicrete.gr (D. Kolokotsa).

0360-1323/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2008.12.007

Section 7 accumulates the conclusions and discusses issues for future research and development.

2. The building energy management system

2.1. Description of the building

The BEMS in which the predictive control scheme is tested, is installed in the Industrial Control Laboratory of the Department of Production and Management Engineering of the Technical University of Crete at Hania, Crete, Greece (35°N latitude). The climatic conditions, i.e., air temperature, humidity and solar radiation on a horizontal surface, of Hania region extracted by METEONORM are illustrated in Fig. 1. The laboratory has 125 m^2 area with almost 3.5 m height, thus 437.5 m^3 volume (see Fig. 2). The building's characteristics including envelope and building services are tabulated in Table 1.

The heating and cooling system is a 30 kW air conditioning system with a cooling power of almost 44 W (38,400 kcal/h). The air conditioning system before the BEMS installation was controlled manually.

The electric lighting in the laboratory uses 94 fluorescent lamps of 58 W and 8 lamps of 18 W.

2.2. The energy management system

The energy management system interconnection is performed using the European Installation Bus-KNX protocol and tools, and is based on a small-scale application presented by the authors' previous work [13]. The monitoring system consists of four sensors for the indoor environment and an outdoor weather station as tabulated in Table 2. The installed actuators are presented in Table 3.

All monitoring and control devices are connected to the European Installation Bus-KNX either directly or by using specific I/O modules (Fig. 3).

3. Predictive control techniques

3.1. Description of the control system

The block diagram of the control system is depicted in Fig. 4 where A represents the actuators and P is the overall BEMS installation. If k is defined as the sample time of BEMS operation then $x(k)$ is the state vector, $y(k)$ is the BEMS' measurements vector, $n(k)$ is the unknown noise for the measurements vector, $u(k)$ the control vector, $d(k)$ the disturbances vector (casual gains, door opening, people smoking, etc.) and x_s is the set-point vector.

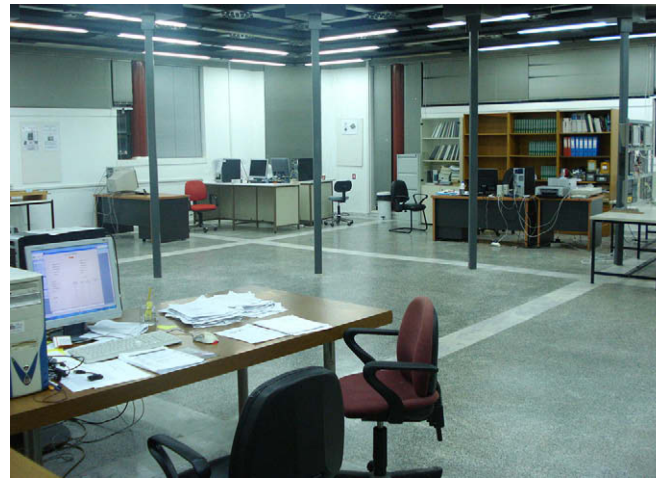

Fig. 2. The laboratory of Department of Production Engineering and Management.

The system is then governed by the following equations:

- Nonlinear state equation: $x(k+1) = f(x(k), u(k), d(k))$.
- Measurements with noise: $y(k) = x(k) + n(k)$.
- Controller's output: $u(k) = g(x_s, y(k))$.

More specifically the state vector is:

$$x(k) = [CO_{2\mathrm{in}}(k) \quad RH_{\mathrm{in}}(k) \quad T_{\mathrm{in}}(k) \quad E_{\mathrm{in}}(k) \;\vdots\; CO_{2\mathrm{out}}(k) RH_{\mathrm{out}}(k) T_{\mathrm{out}}(k) E_{\mathrm{out}}(k)]^T = \left[x_{\mathrm{in}}^T(k) \quad x_{\mathrm{out}}^T(k)\right]^T \tag{1}$$

where $CO_{2\mathrm{in}}(k)$ is the indoor CO_2 concentration (in ppm), $RH_{\mathrm{in}}(k)$ is the indoor relative humidity (%), $T_{\mathrm{in}}(k)$ is the indoor temperature (°C), $E_{\mathrm{in}}(k)$ is the indoor illuminance (lx), $CO_{2\mathrm{out}}(k)$ is the atmospheric CO_2 concentration (ppm), $RH_{\mathrm{out}}(k)$ is the outdoor relative humidity (%), $T_{\mathrm{out}}(k)$ is the outdoor temperature (°C) and $E_{\mathrm{out}}(k)$ is the outdoor illuminance (lx).

The control vector is

$$u(k) = [W(k) \quad L(k) \quad S(k) \quad AC(k)]^T \tag{2}$$

where S is shading output (0: fully closed, 1: fully opened, linear output), W is window opening output ((0: fully closed, 1: fully

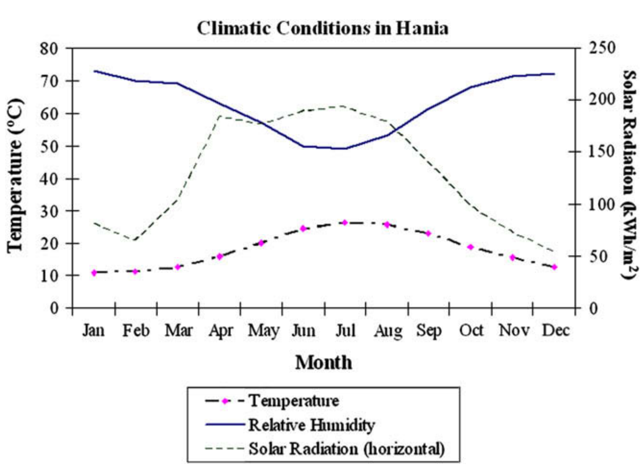

Fig. 1. The climatic conditions in Hania, Crete, Greece.

Table 1
The building's characteristics.

Layer[a]	Material	Depth (m)
Building's envelope characteristics		
External walls		
1	Plaster board	0.013
2	Concrete block	0.035
3	Plaster board	0.013
Floor/roof		
1	Concrete slab	0.030
Door		
1	Iron	0.035
Windows: single glazed iron framed		
1	Glass	0.003
Building services		
Air conditioning		Split type
Electric lighting		Fluorescent lamps

[a] From internal layer to external.