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Energy savings and guaranteed thermal comfort in hotel rooms through nonlinear model predictive controllers

Adriana Acosta[a], Ana I. González[a], Jesús M. Zamarreño[b,*], Víctor Álvarez[c]

[a] Departamento de Automática y Computación, Instituto Superior Politécnico José Antonio Echeverría, La Habana, Cuba
[b] Departamento de Ingeniería de Sistemas y Automática, EII, Universidad de Valladolid, C/Dr. Mergelina s/n, 47011 Valladolid, España
[c] Hotel Meliá Habana, Ciudad Habana, Cuba

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ABSTRACT

This paper presents the results obtained during the synthesis of nonlinear predictive controllers dedicated to the energy management of centralized air conditioning systems in the rooms from two city hotels. The model for predictions is based on the Radiant Time Series (RTS) method. To satisfy the thermal comfort required by the occupants, an adaptive model is considered explicitly in the economic objective function of the predictive controller. Historical records of electrical consumption from the two hotel facilities are used for comparing the performance of the controllers. Results obtained in simulation using real data as inputs show an improvement in energy consumption while maintaining the thermal comfort.

1. Introduction

Automatic control advanced techniques provide an opportunity for significant energy savings in the operation of air conditioning systems by improving the energy efficiency. The use of these techniques responds to the need from many productive sectors that require reliable techniques for process operation with high efficiency and high degree of flexibility [1].

It is well known that despite all the energy saving policies implemented so far, energy consumption from air conditioning systems in buildings represents around 40% of the total volume of any modern city [2]. From economic and environmental reasons, it is necessary to apply new control techniques for obtaining better results in this field.

On the other hand, we must take into account the existing conflict between the thermal comfort of the occupants inside the rooms and the energy required to provide these conditions. The use of advanced control techniques that consider a model of energy predictions to regulate the management of the Heating, Ventilation and Air Conditioning (HVAC) systems is a subject of great interest for researchers and manufacturers [3–13].

This paper aims at energy efficiency in centralized air conditioning systems installed in tourist accommodation buildings. The main interest comes from the rapid development of this sector in the Caribbean and the constant need for reducing operating costs. The design of a Non-Linear Predictive Controller (NLPC) [14] for optimizing the electrical energy consumed by the centralized air conditioning system for the rooms at two hotels in Havana, Cuba, is presented. The energy prediction model, used in the NLPC, is a first principles model, based on the Radiant Time Series (RTS) method for determining the cooling load [15].

Based on previous works [16–18], the main contribution of this paper is the explicit consideration of the thermal comfort conditions as constraint in the temperature of the rooms in the formulation of the NLPC. The average outdoor air temperature for the current month is used [19] as a way of including the comfort conditions in the formulation.

This paper consists of 5 sections. This introduction presents the general motivation. The second section describes and compares the two hotel facilities according to their main characteristics. In the third section, the methodology used to achieve the objectives and the formulation and parameterization of the NLPC are explained. The fourth section shows the main results and their analysis, and finally, in the last section, the conclusions are summarized.

* Corresponding author.
E-mail addresses: adriana.virginia@electrica.cujae.edu.cu (A. Acosta), anita@electrica.cujae.edu.cu (A.I. González), jesusm@autom.uva.es (J.M. Zamarreño).

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Table 1
Variables and parameters.

Nomenclature	
A	Surface area, [m^2]
A_0,A_1,A_2	Chillers coefficients
c_0, c_1,... c_{23}	Conduction time factors
C_k	Cost per kWh according to the corresponding fare, [USD]
COP	Chiller Coefficient Of Performance
E_t	Total solar radiation incident on surface, [W/m^2]
h_o	Coefficient of heat transfer by long-wave radiation and convection at outer surface, [W/m^2.K]
k	Current hour
N_c	Control horizon
N_{p1}	Initial value for the prediction horizon, [h]
N_{p2}	Final value for the prediction horizon, [h]
Opt_{time}	Required time for obtaining the sequence of optimal control actions, [s]
P	Electrical power consumed by the chiller, [W]
q	Hourly conductive heat gain for the surface, [W]
Q_{evap}	Thermal cooling capacity of the evaporator, [W]
q_i	Conductive heat input for the surface, [W]
Q_r	Radiant cooling load, [W]
q_r	Radiant heat gain, [W]
Q_s	Cooling load for each occupied hotel room, [W]
Q_{sal}	Total cooling load for all occupied rooms, [W]
r_0,r_1, ... r_{23}	Radiant time factors
T_{cold}	Chilled water supply temperature to the building, [°C]
$\overline{T_{cold}}$	Hourly vector (24 elements) of current month average of chilled water supply temperature to the building, [°C]
T_c	Comfort temperature, [°C]
T_e	Sol-air temperature, [°C]
T_{int}	Room air temperature optimized by the NLPC, [°C]
$T_{int,s}$	Room air temperature for each room, [°C]
T_{out}	Outdoor air temperature, [°C]
$\overline{T_{out}}$	Hourly vector (24 elements) of current month average of outdoor air temperature, [°C]
T_{ret}	Total return chilled water temperature, [°C]
$T_{ret,s}$	Return chilled water temperature for each room, [°C]
U	Overall heat transfer coefficient for the surface, [W/m^2 K]
u_{adj}	Adjustment term for comfort conditions, selected by expert criteria, [°C]
α	Weights for the output along the horizon in the objective function
α_r	Absorptance of surface for solar radiation
β	Weights for control actions increments in the objective function
Δ_{cost}	Potential savings in electrical consumption of the chiller units obtained by simulation, [kW]
ΔR	Difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by a black body at outdoor air temperature, [W/m^2]
Δt	Sampling time, [h]
ε	Hemispherical emittance of surface
γ	Weights for control actions variations with respect to some expert based reference values

At Table 1, all variables and parameters used in this work are summarized.

2. Description and energy consumption of the hotels

In this work, two five-star city hotels were selected: the "Meliá Habana" hotel and the expanding of the "Parque Central" hotel, known as "La Torre". The "Meliá Habana" hotel has been the main interest in previous research [16–18]; it is located on the northwest coast of the city of Havana in Cuba, and it has some level of automation and proper management of historical operation records. This hotel has been in operation for more than 16 years.

The "Parque Central La Torre" hotel is 10 years younger than the "Meliá Habana" hotel [20]. Data characterizing the two buildings are listed at Table 2.

For the "Meliá Habana" hotel, temperature measurements were taken with a PT100 calibrated thermometer (HI92840C) from Hanna Instruments with an accuracy of ±0.1 °C. Measurements were taken at the room balcony and inside the room.

For the "Parque Central" hotel, temperature measurements were taken with a HD2127 thermometer from Riels Instruments with an accuracy of ±0.01 °C. Measurements were taken at the room balcony and inside the room number 1702 located at the seventh floor.

Fig. 1 shows the behavior of the power consumption to the Hotel Daily Occupation (HDO) ratio during 2012 for each hotel.

Electrical consumption at each hotel follows the distribution shown at Figs. 2 and 3. It can be seen that the air conditioning system (chiller) amounts up to 61% of the total consumption for the "Meliá Habana" hotel and 48% of the total consumption for the "Parque Central La Torre" hotel.

For this reason, our research has been focused on the air conditioning system, based on the criteria that the accommodation in a hotel should be the main source of income.

3. Methodology

The procedure used in the design and implementation of the nonlinear controller for reducing energy consumption consists of the following steps:

a Estimation of the cooling load for each hotel room using a predictor based on the method of radiant time series [15] already published in [17].
b Modeling the power consumption of the chiller units as a function of the estimated cooling load.
c Design and tuning of the nonlinear predictive controller.
d Calculation of the economic results obtained from the application of the predictive controller in simulation.

The model is composed of two main elements: the predictor for the cooling load and the model for the chiller units.

3.1. Cooling load predictor based on RTS method

At Fig. 4, a diagram of the prediction model is shown. At every hour, input values must be measured and updated: for example, the outdoor air temperature, the room air temperature, the chilled water supply temperature and the number of occupied rooms. The room air temperature and the return chilled water temperature are different for each room since there exist specific sensors at every room.

Values for outdoor air temperature and chilled water supply are the same for all rooms in the hotel. As inputs, the current hour, the current month and the Day Light Time (DLT) are inputs to the model too. With all this information available, the cooling load $Q_s(k)$ (1) for each room s at time k is calculated by estimating the different heat gains from internal and external sources. The hotel cooling load $Q_{sal}(k)$ [16] is totalized over all the occupied rooms (2).

$$Q_s(k) = \mathrm{PredRTS}(k, Month, DLT, T_{int,s}, T_{out}, T_{cold}, T_{ret,s}), \quad s = 1, \ldots, HDO \tag{1}$$

$$Q_{sal}(k) = \sum_{s=1}^{HDO} Q_s(k) \tag{2}$$

The total return chilled water temperature is calculated as an average of the return chilled water temperature for each room (3). Only occupied guest rooms are considered for calculation of this average.

$$T_{ret} = \frac{\sum_{s=1}^{HDO} T_{ret,s}}{HDO} \tag{3}$$