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A comparison of thermal comfort predictive control strategies

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ABSTRACT

Most of the time, people perform their daily activities inside buildings. Thus, an important factor is to look for a tradeoff between energy saving and user welfare, since lack of poor indoor comfort has a direct effect on users' productivity and an indirect effect on energy efficiency. The use of appropriate control strategies can highly contribute to this purpose. This paper presents a comparison among several predictive control approaches, that allow to obtain a high thermal comfort level optimizing the use of an HVAC (Heating, Ventilation and Air Conditioning) system by means of different cost functions. Real results obtained in a solar energy research centre are included and commented.

1. Introduction

Nowadays, saving on energy consumption in use in or construction of buildings and energy efficiency inside them are topics that are receiving great attention by companies and from a scientific and technical point of view [1]. In accordance with recent studies, energy consumption in buildings represents about 40% of the total world energy consumption, more than half used by HVAC (Heating, Ventilation and Air Conditioning) systems [2–4].

However, energy saving must not put users' welfare at risk [5], and hence, it is necessary to use appropriate control strategies on HVAC systems (together with new innovations in building design) with the main objective of providing comfortable environments from a thermal, visual, and indoor-air quality points of view, and minimizing energy consumption at the same time [6].

Thus, this paper presents a predictive control system which allows to obtain a high thermal comfort level taking energy costs into account. The proposed control strategy is focused on from two different points of view.

First, a hierarchical predictive control strategy is employed. In this case, an upper layer, which is defined with a predictive control framework, will be dedicated to optimize the indoor air temperature references that would be necessary to reach an appropriate comfort. Then, a lower layer will follow these references by varying the system fan-coil through PID (Proportional Integral Derivative [7]) controllers. On a second approach, the control problem will be directly dealt with using classical predictive control strategies [8], employing only one layer. Now, the predictive control algorithm optimizes the system comfort by generating adequate process inputs (the fan-coil of the HVAC system).

Different cost functions have been evaluated for both approaches. Therefore, the main goal of this study is twofold: (i) to select the most appropriate cost function for this system, achieving a tradeoff between the use of the HVAC system and users' thermal comfort; and (ii) to demonstrate that it is possible to develop high performance controllers for thermal comfort through using on-off actuators, such as the fan-coil of the HVAC system. The different control systems presented in this work have been tested in a solar energy research centre, the CDdI CIESOL-ARFRISOL building, although the results obtained with these control systems can be extrapolated to any building with a suitable sensor network and an HVAC system.

The paper is organized as follows: Section 2 briefly introduces the facilities where this work has been developed, the CDdI CIESOL-ARFRISOL building. Section 3 includes a brief overview of the thermal comfort concept and its estimation procedure, the PMV index. In Section 4, the different control strategies are described. Section 5 is devoted to presenting the obtained results. Finally, in Section 6, the main conclusions are summarized.

2. System description

The CDdI-CIESOL-ARFRISOL (http://www.ciesol.es) research centre on solar energy, which is shown in Fig. 1, has two floors with a total surface of 1071.91 m^2 and it is located inside the campus of the University of Almería (South East of Spain). This research centre

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was built following a bioclimatic architecture criteria, where HVAC systems are based on solar cooling [9] using a solar collectors field, a hot water storage system, a boiler, and absorption machine with its refrigeration tower. Moreover, this building has all its rooms monitored by means of a sensor network, whose data is stored in a database through an acquisition system [10]. In addition, there is a meteorological station placed on the roof of the building, which is sensing outside temperature, humidity, CO_2 level, solar radiation, and wind speed and direction. The most representative rooms of the building have been equipped with actuators to control the comfort inside the building (HVAC systems, automated windows opening and shading devices), as shown in Fig. 1.

Besides that, this is one of the five buildings (CDdI) studied in the project ARFRISOL, which is a singular strategic project of the Spanish R&D plan 2004–2011 financed by EU-ERDF funds and by the Spanish Ministry of Science and Innovation (MICINN). This project is headed by the Energy Efficiency Unit of CIEMAT and relies on the participation of research centres such as CIEMAT, the University of Almería or the University of Oviedo, the most important Spanish construction companies, and some of the Spanish solar technological companies. The five buildings studied within this project are located in Spain, at the University of Almería (South-East), Plataforma Solar de Almería (South-East), in CIEMAT-Madrid (Center), in Barredo-Asturias Foundation (North-West), and in CEDER-CIEMAT-Soria (North-East) (http://www.arfrisol.es).

3. Thermal comfort

In accordance with *ISO 7730* [11] and *ASHRAE 55* [12] international standards, thermal comfort can be defined as: “That condition of mind which expresses satisfaction with the thermal environment” [13]. However, this definition may be considered ambiguous, as it leaves the meaning of condition of mind and *satisfaction* open, but it emphasizes that comfort is a cognitive process influenced by different kinds of processes, such as, physical, physiological or even psychological aspects [14].

Furthermore, comfort depends on several circumstances, such as the place where the human is, the reason why he is in that place, the season of the year, etc. However, according to different studies in this area, although climates, living conditions, and cultures differ around the world, the temperature that people choose for comfort under similar conditions of clothing, physical activity, relative humidity, and air velocity is very similar [14].

3.1. Thermal comfort indexes

Many authors have studied the calculation problem of the comfort conditions in a certain environment [15–19]. The most extended index is the PMV (*Predicted Mean Vote*), which has been developed by Fanger in the seventies in order to obtain a model for the thermal comfort of a human being. The PMV index predicts the mean response about thermal sensation of a large group of people exposed to certain thermal conditions for a long time [20]. The value of PMV index is a seven-point thermal sensation scale: 0 neutral, ± 1 slightly warm/cool, ± 2 warm/cool, ± 3 hot/cold. To ensure thermal comfort in a certain environment, different standards recommend to maintain the PMV at level 0 with a tolerance of ± 0.5 [21].

PMV is defined by six variables that are shown in Table 1. On the one hand, most of these variables can be obtained in a simple way [22]. More specifically, air temperature, air velocity, and air humidity are obtained in a direct way through specific sensors. On the other hand, clothing insulation and metabolic rate are not estimated variables, they are determined by the user situation when PMV index is estimated. Thus, if this situation is known, the values of these variables can be found in different standards [11,12]. For example, the clothing insulation and the metabolic rate associated with an office environment are 1.0 clo and 1 met, respectively.

Table 1
Variables which define thermal comfort.

Parameter	Symbol	Range	Unit
Metabolic rate	M	0.8–4	met (W/m^2) *
Clothing insulation	I_{cl}	0–2	clo (m^2 °C/W) **
Air temperature	y_T, (t_a)	10–30	°C
Mean radiant temperature	$\bar{t}_r$	10–40	°C
Air velocity	v_a	0–1	m/s
Air humidity	y_{HR}	30–70	%

* 1 met = 58.15 W/m^2.
** 1 clo = 0.155 m^2 °C/W.

Metabolic rate (M) can be defined as the energy consumed by humans in a certain period of time, and, mean radiant temperature ($\bar{t}_r$) as the uniform temperature of an imaginary enclosure in which radiant heat transferred from the human body equals the radiant heat transferred in the actual non-uniform enclosure. The procedure to estimate this variable is widely described in [14].

Furthermore, human thermal sensation is strongly connected with the energy balance of the body, considering this a whole entity, where the human body is in a heat balance situation, i.e., the heat produced by metabolism must be equal to the amount of heat lost by the human body. Therefore, when the human body is in this balance situation, he/she is in ideal conditions of comfort and the PMV index is equal to 0 [20]. PMV index can be estimated according to this balance and the six previous variables just as expressed in (1).

$$\text{PMV} = y_{\text{PMV}} = [0.303 \exp(-0.036M) + 0.028] \cdot L \tag{1}$$

In the previous equation, L is the thermal load in the human body [W/m^2], defined as the difference between the internal heat production and the heat lost which occurs when the person is in a thermal situation, and M is the metabolic rate [W/m^2]. Thermal load, L, is estimated using (2). In the following equations:

Q: external work [W/m^2], that is, the developed work performed by muscles doing a certain task.
y_T: air temperature [°C].
p_a: partial water vapor pressure in the air [Pa]. Relative humidity, y_{HR}, is the relation, expressed in percentage, between partial water vapor pressure in the air and saturated water vapor pressure from a temperature.
t_{cl}: clothing surface temperature [°C].
convective heat transfer coefficient [m^2 °C/W].
I_{cl}: clothing insulation [m^2 °C/W].
clothing area factor [−].
air velocity [m/s].

$$\begin{aligned} L = {} & (M-Q) - 0.0014 \cdot M \cdot (34 - y_T) \\ & - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-Q) - p_a] \\ & - 0.42 \cdot (M - Q - 58.15) - 1.72 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) \\ & - 39.6 \cdot 10^{-9} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - y_T) \end{aligned}$$

where

$$\begin{aligned} t_{cl} = {} & 35.7 - 0.028(M-Q) \\ & - 0.155 \cdot I_{cl} \cdot [39.6 \cdot 10^{-9} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] \\ & + f_{cl} \cdot h_c \cdot (t_{cl} - y_T)] \end{aligned} \tag{3}$$