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Hybrid PID-fuzzy control scheme for managing energy resources in buildings

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ABSTRACT

Both indoor temperature regulation and energy resources management in buildings require the design and the implementation of efficient and readily adaptable control schemes. One can use standard schemes, such as "on/off" and PID, or "advanced" schemes, such as MPC (Model Predictive Control). Another approach would be considering artificial intelligence tools. In this sense, fuzzy logic allows controlling temperature and managing energy sources, taking advantage of the flexibility offered by linguistic reasoning. With this kind of approaches, both the specific use of a building and the specificities of a proposed energy management strategy can be easily taken into account when designing or adjusting the control scheme, without having to model the process to be controlled. PID controllers being commonly used in buildings engineering, the proposed control scheme is built on the basis of a PID controller. This allows implementing the scheme even if a control system based on such a controller is already in use. So, a hybrid PID-fuzzy scheme is proposed for managing energy resources in buildings, as the combination of two usual control structures based on PID and fuzzy controllers: the "parallel" structure (according to the current dynamical state of the considered process, either the PID or the fuzzy controller is selected) and the "fuzzy supervision" of a PID controller. To test the scheme in simulation, a building mock-up has been built, instrumented and modeled. Finally, criteria describing the way energy is used and controlled in real-time have been defined with the aim of evaluating both the proposed strategy and the control scheme performance.

1. Introduction

Managing energy resources in buildings is fully related to both the development and the in situ implementation of efficient control schemes. Controlling energy systems and/or actuators allows ensuring indoor comfort and, to a lesser extent, reducing energy consumption. Security and fault detection are also under consideration. Several tools, such as Multi Agent Control Systems (MACS) have already been developed with the aim of responding to the just-mentioned problematic [1]. Unfortunately, these tools are hard to develop and implement.

Parameters to be controlled can be classified into multiple categories. Because people spend about 90% of the time inside buildings, indoor parameters, such as brightness, air quality and movement, humidity or thermal ambience, affect their health, morale or productivity. That is why ensuring thermal comfort (generally defined as follows: "that condition of mind which expresses satisfaction with the thermal environment" and usually referred of whether someone is feeling too cold or too hot) is essential because of its psychological implications. In some cases, people may refuse to live or to work in a particular environment. One speaks of "Sick Building Syndrome" (SBS) [2–4], as a combination of ailments associated with an individual's place of work (office building) or residence. A key-point, when managing energy resources in buildings, is that ensuring thermal comfort, controlling the above-mentioned indoor parameters, while reducing energy consumption is not an easy task. Both considerations seem to be in opposition.

Whatever the meaning we give to it and because of its subjectivity, thermal comfort is difficult to define as a range of environmental and personal factors. That is why a common approach deals with the "Predicted Mean Vote" (PMV) (on the following thermal sensation scale: +3 is "very hot", +2 is "hot", +1 is "relatively hot", 0 is "neither hot nor cold", −1 is "relatively cold", −2 is "cold" and −3 is "very cold") of a large population of people exposed to a certain environment. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation. The PMV equation uses a steady-state heat balance for the human body and postulates a link between the deviation from the minimum load on heat balance effector mechanisms and thermal comfort vote. The greater the load, the more the comfort vote deviates from zero. PMV is arguably the most widely used thermal comfort index today. PPD is the "Predicted Percent of Dissatisfied" people at each PMV [5,6]. However, this index is not always easy to use and focuses on human feeling only. So, it is not well adapted to considerations such as control performance or energy consumption. That

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Nomenclature

$\%_{FE}$	percentage of the fossil energy consumed compared with the total energy used
I_C	comfort criterion
I_P	performance criterion
E_{RE}	renewable energy consumed (Wh m^{-2})
E_{FE}	fossil energy consumed (Wh m^{-2})
E_{TOT}	total energy consumed (Wh m^{-2})
T_{SP}	temperature set-point (°C)
T_m	building's indoor mean temperature (°C)
U_{walls}	thermal losses due to walls (W m^{-2}°C^{-1})
U_{roof}	thermal losses due to the roof (W m^{-2}°C^{-1})
U_{door}	thermal losses due to doors (W m^{-2}°C^{-1})
$U_{windows}$	thermal losses due to windows (W m^{-2}°C^{-1})
U_{floor}	thermal losses due to the floor (W m^{-2}°C^{-1})
T_i	indoor temperature measured by the ith sensor (°C)
T_{out}	outdoor temperature (°C)
u_1	power of the first heat source (W)
u_2	power of the second heat source (W)
α_i	inertia of temperature T_i
β_{i1}	influence of the first heat source on temperature T_i (first parameter)
ρ_{i1}	influence of the first heat source on temperature T_i (second parameter)
β_{i2}	influence of the second heat source on temperature T_i (first parameter)
ρ_{i2}	influence of the second heat source on temperature T_i (second parameter)
γ_i	influence of outdoor temperature on temperature T_i
T_{mes}	experimental temperature (°C)
T_{mod}	modeled temperature (°C)
W_{RE}	renewable energy warmer
W_{FE}	fossil energy warmer
U_{RE}^{PID}	power of W_{RE} estimated by the PID controller (W)
U_{FE}^{PID}	power of W_{FE} estimated by the PID controller (W)
U_{RE}^{FLC}	correction to be applied to U_{RE}^{PID} (estimated by the by the first fuzzy module) (W)
U_{FE}^{FLC}	power of W_{FE} estimated by the second fuzzy module (W)
U_{RE}	$U_{RE} = U_{RE}^{PID} + U_{RE}^{FLC}$ (W)
ε	$\varepsilon = T_{SP} - T_m$ (°C)
K_{RE}	denormalization gain applied to U_{RE}^{FLC}
K_{FE}	denormalization gain applied to U_{FE}^{FLC}
K_P	proportional gain
K_I	integral gain
K_D	derivative gain

is why, usually, the building's Energy Performance Indicator (EPI) (kWh m^{-2} year^{-1}) is also calculated [7,8]. Unfortunately, this indicator is only able of expressing the amount of energy consumption, without any explanation. It does not both dissociate the various energy consumptions components and explain how energy is consumed in buildings. As a consequence, proposing new and effective control approaches allowing ensuring indoor comfort, taking into consideration the previously mentioned and hard-to-handle parameters, while reducing significantly energy consumption, has become mandatory.

Standard control schemes, such as "on/off" and PID, are widely used in building engineering [9–11]. As an example, on/off controllers are used for indoor temperature regulation but, in this case, energy consumption is high because of both significant fluctuations and frequent set-point overshoots. This kind of control schemes perform poorly in some applications or environments (such as disturbed environments) and do not in general provide optimal control. PID controllers are feedback (or closed-loop) controllers with constant parameters and no direct knowledge of the considered process. When used alone, they usually give poor control performance for large time-delay process, in case of process noise or in the presence of non-linearities [12,13]. Usually, the control system performance is improved by cascading multiple PID controllers [14] or by combining feedback and feed-forward (or open-loop) controllers [15]. In the second case, knowledge about the considered system can be fed forward and combined with the PID output to improve the overall system performance. Another valid approach would be considering, instead of (or in addition to) the just-mentioned standard control schemes, "advanced" schemes or artificial intelligence tools [16–18]. In this sense, optimal [19,20], predictive [21,22] and adaptative [23,24] controllers were used for both ensuring thermal comfort and limiting set-points overshoots, as the only way to save energy. Because these controllers are model-based controllers, one needs to model the considered buildings. However, every building has a specific non-linear thermal behavior related to the construction materials used, its structure, its use and its environmental condition. As a consequence control schemes found in the literature always focus on a specific kind of buildings [25,26]. As previously mentioned, artificial intelligence tools can also be used for controlling influential parameters in buildings. In this sense, fuzzy adaptative controllers have been successfully applied to heating [27,28], with the aim of maximizing both energy efficiency and thermal comfort, visual comfort [29,30] or natural ventilation [31], one of the most interesting ways for improving buildings' energy performance [32–35]. In the same way or as complementary approaches, artificial neural networks and neuro-fuzzy systems were used as control tools [36–39], for forecasting various environmental parameters, such as indoor temperature, illuminance or relative humidity [40,41], or for modeling inhabitants' behavior related to energy use [42–44].

The present paper deals with the development of an indoor temperature controller, allowing managing energy resources in buildings. The main objective of the proposed strategy is optimizing energy performance while ensuring thermal comfort, using the developed control scheme. One can highlight, and this is a key point, that we consider, in opposition of what one can find usually in the literature [1], buildings with both fossil and renewable energy resources (one can speak of "multi-energy" buildings) and we want the control scheme to be easily adaptable to different uses of buildings. On another hand and because PID controllers are commonly used in buildings engineering, the proposed control scheme is built on the basis of a PID controller. This allows implementing the scheme even if a control system based on such a controller is already in use and finding ways for improving its performance. With the aim of both taking into account expert knowledge about the just-mentioned considerations and applying the proposed strategy to multi-energy buildings, a hybrid PID-fuzzy controller is proposed, as the combination of two usual control structures based on PID and fuzzy controllers: the "parallel" structure (according to the current dynamical state of the considered process, either the PID or the fuzzy controller is selected) and the "fuzzy supervision" of a PID controller [45]. A building mock-up has been built, instrumented and modeled to test the proposed controller in simulation. Instrumentation consists of height temperature sensors and two resistors used as heat sources. Finally, and because both the PMV and the EPI are sometimes hard to handle and only provide partial information, criteria describing the way energy is used and controlled in real-time have been defined with the aim of evaluating both the proposed energy management strategy and the hybrid control scheme performance. The present paper mainly focuses on the impact on these criteria and on energy consumption of both the