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Assessment of internal and external disturbances on the fuzzy-based thermal control of a sub-scaled building testbed

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Abstract. This experimental study follows on our previous work on the development of robust fuzzy-based thermal control strategies of a multi-room sub-scaled building testbed. In the present analysis, the focus is placed on testing the robustness of the fuzzy controller under internal and external disturbances, as it deals with maintaining specific setpoint values of room temperatures. The testbed has eight rooms, distributed on two floors, with a cooling unit that supplies cool air to each room, and eight 40 W light bulbs serving as heat sources. T-type thermocouples gather the temperature data, and eight dampers deliver the airflow. The controller uses information about the difference between setpoint and actual temperatures, their derivative, and their cumulative integral. The fuzzy sets and if-then rules are built based on experimental data, and a Mamdani inference method is used to provide the inputs to the actuators. Results from experimental tests show that the fuzzy control strategy can handle the different types of disturbances while maintaining the room setpoints.

1. Introduction

The use of fossil fuels as a source of energy has been key for the industrialization of the world society, but resulting pollutants from energy conversion processes have also led to global climate change [1]. This critical problem can be addressed by improving the design and use of energy systems, particularly those used in urban areas. An important example is that of the residential and commercial building sector, which uses nearly 40% of the global energy consumption [2].

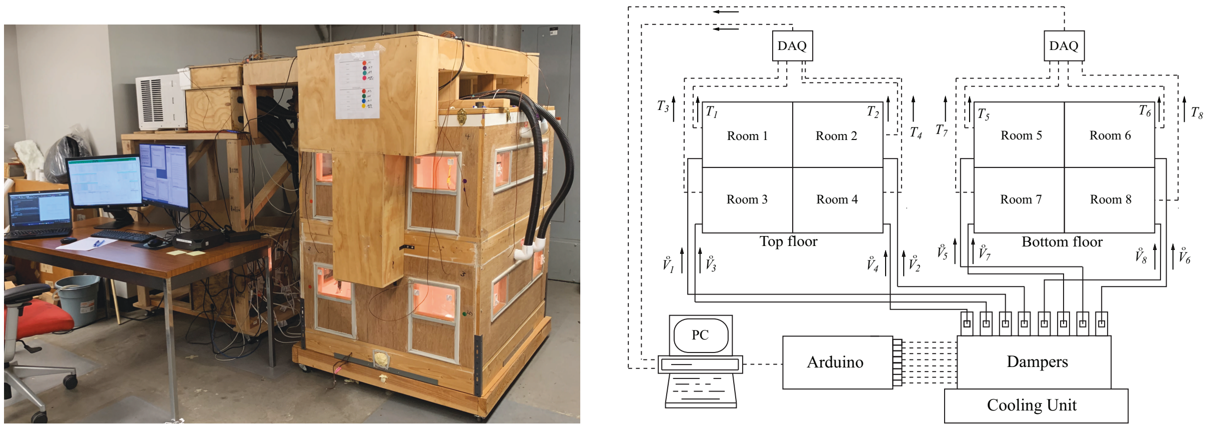
The design and control of HVAC devices and associated processes in buildings, are essential if the goal is to use energy in an effective manner. However, these tasks are demanding due to system complexity, which prevent using accurate compact models [3]. For instance, for control purposes in multi-room buildings, models based on PDEs are extremely difficult to solve in real time, so that the thermal engineer has to rely on PID-like controllers, Though the PID can be easily implemented and tuned [4], lack of robustness is one of its main drawbacks that can degrade controller performance [5]. Thus, alternative thermal control strategies for buildings are necessary.

The use of fuzzy logic-based control schemes has grown in the area of thermal control engineering, mainly due to their ability to use human experience to execute the control actions. Fuzzy logic [6], has also been used to effectively describe the behavior of complex systems in many application areas. Examples include the thermal control of heat exchangers [7], heat pumps [8], and photovoltaic systems [9], among others. However, only few studies have focused on the thermal control of buildings, mainly using numerical data [10, 11].

In this experimental study we expand upon our previous work upon the thermal control of a multi-room building testbed using fuzzy logic [12], with emphasis on the robustness of the controller to internal and external disturbances. Thus, a short description of the facility is presented first, followed by a brief introduction of the fuzzy logic technique. The fuzzy control scheme used to regulate the room temperatures in the building is provided next. Finally, the results on the response from the fuzzy controller to either internal or external disturbances, demonstrate that the control strategy can effectively achieve the corresponding setpoints. However, there is a limit beyond which the system becomes uncontrollable.

2. Experimental Testbed

The experimental tests are done in a sub-scaled building testbed that has eight rooms of same size placed into two floors, as shown in Fig. 1. Wood and insulated drywall are used for the structure and the interior walls, respectively, with overall dimensions: 1.2 m × 0.92 m × 1.1 m in height. 40 W incandescent light bulbs provide energy to the rooms, while an external HVAC unit supplies cold air to each room. Two type-T thermocouples measure average air temperatures in each room, whereas the air flow rate is regulated by eight dampers that are operated by the fuzzy controller. LabVIEW serves as interface between the testbed and the controller (coded in MATLAB), transferring temperature readings and the corresponding control outputs to modify the angle of each damper in the outlet manifold of the cooling unit. Temperature readings $T_a(t)$, of each room, acquired at constant time intervals, are stored for further analysis.



(a) Picture.　(b) Schematic.

Figure 1. Sub-scaled building testbed.

3. Fuzzy Control

3.1. Introduction to Fuzzy Logic

Fuzzy logic (FL) uses linguistic variables and expert-based rules to describe the behavior of complex systems. Because of is its ability to handle vagueness and imprecision in the data to solve a particular problem, since its development [6, 13], it has been used in several applications, including those related to system and process control [7, 14]. The concept of fuzzy sets relies on a continuous scale of membership of an element belonging to a specific set (e.g., either fully-, partially- or not-belonging), and provides a generalization of the concept of a strict binary crisp set, where an element either belongs to the set or does not. In the context of air temperature

T_a, e.g., using crisp sets, T_a "is" either hot or it "is not"; but using fuzzy sets, then T_a, can be described anywhere in between 'very cold', 'cold', 'warm', 'hot', or 'very hot'. Mathematically, these representations are defined, respectively, for the membership functions, as $\mu_A(T_a) = \{0, 1\}$ and $\mu_A(T_a) \in [0, 1]$. After fuzzification (i.e., a crisp value is mapped into fuzzy sets via their membership functions), the inference engine uses knowledge about the process/system from the expert, and generates a cumulative fuzzy output, which then is mapped back (i.e., defuzzification process), into a crisp value. In the present work, this last step is done via an inference system developed by Mamdani [15]. Additional information about its background and applications are in [14, 16], among other monograms.

3.2. Fuzzy Controller
For thermal control of the building testbed, the key variables are: air flow rates, $\dot{\mathcal{V}}_a$, and room temperatures, $T_a(t)$. Using fuzzy logic, both will be represented as linguistic variables to describe their dynamic state. Thus, following Baltazar et al. [12], the overall control system has eight single-input single-output (SISO) control loops, each shown in Fig. 2. The control input from each controller is the air flow rate $\dot{\mathcal{V}}_a(t)$, while room air temperature $T_a(t)$, is the system output.

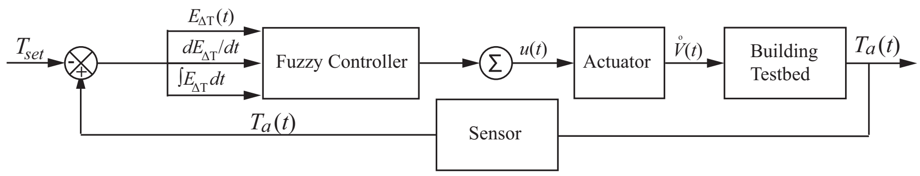
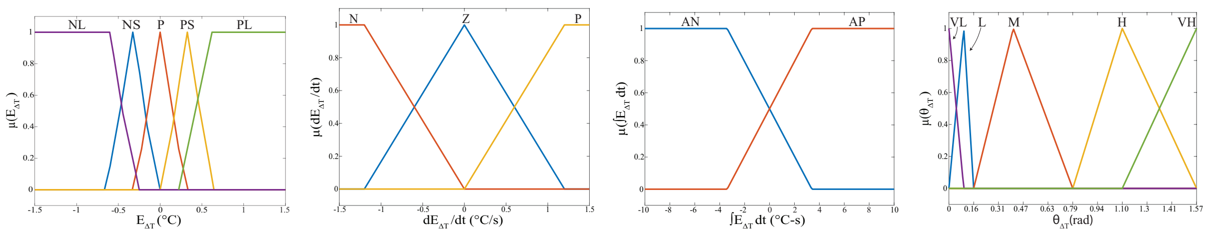


Figure 2. Closed-loop fuzzy control.

In agreement with the work of Pacheco-Vega et al. [7], all controllers are built with a linear combination of information about the error between the setpoint, T_{set}, and the actual room temperatures, $T_a(t)$; i.e., $E_{\Delta T} = T_{set} - T_a(t)$, its difference over time $dE_{\Delta T}/dt$, and the integral of such error over a specified period of time, $\int E_{\Delta T} dt$. The corresponding membership functions and fuzzy sets are shown in Fig. 3. For $E_{\Delta T}$ the fuzzy sets have 2 trapezoidal and 3 triangular membership functions in the range $[-10, 10]^\circ$C. For $dE_{\Delta T}/dt$ these are composed of 2 trapezoidal and one triangular membership functions in the range $[-1.5, 1.5]^\circ$C/s. The fuzzy sets for $\int E_{\Delta T} dt$ have 2 trapezoidal membership functions in the range $[-10, 10]^\circ$C-s. Finally, the fuzzy sets for the angle $\theta_{\Delta T}$ have 5 triangular membership functions in the range $[0, 1.57]$ rad ($\theta_{\Delta T} = 0$ rad equal a fully-closed damper; $\theta_{\Delta T} = 1.57$ rad equal a fully-open damper).



(a) $E_{\Delta T}$. (b) $dE_{\Delta T}/dt$. (c) $\int E_{\Delta T} dt$. (d) $\theta_{\Delta T}$.

Figure 3. Fuzzy sets and membership functions for fuzzy controller.

The set of inference rules are shown in Tables 1 and 2 where, in accordance with Fig. 3, the values for the linguistic variable $E_{\Delta T}$ are 'NL', negative large, 'NS', negative small, 'Z', zero,'PS', positive small, 'PL', positive large; whereas those for $dE_{\Delta T}/dt$, are 'N', negative, 'Z', zero, and 'P', positive, with 'NR' being a no-rule. Finally, for $\int E_{\Delta T} dt$ the values of the fuzzy sets are 'NL', negative large, 'AN', always negative, and 'AP', as always positive. To defuzzify the outputs and generate a crisp value to the air flow actuators (dampers), the well-known Mamdani inference method [15] is used here.

Table 1. Decision matrix 1 for $\theta_{\Delta T}$.

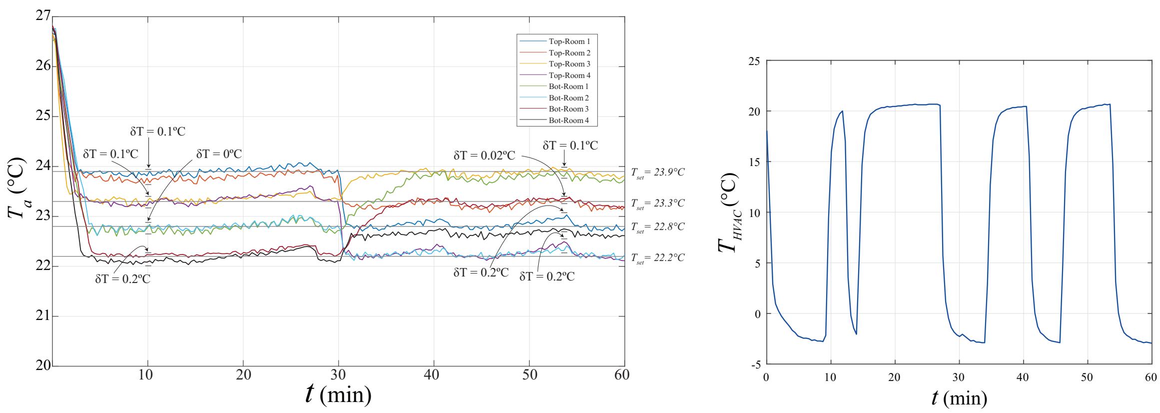
$\theta_{\Delta T}$	↘	$E_{\Delta T}$: NL	NS	Z	PS	PL
$dE_{\Delta T}/dt$	N		VL	L		
	Z	VL	VL	L	L	VH
	P		M	H	H	
	NR	VL	L	M	H	VH

Table 2. Decision matrix 2 for $\theta_{\Delta T}$.

$\theta_{\Delta T}$	↘	$\int E_{\Delta T} dt$: AN	AP
$dE_{\Delta T}/dt$	N	H	L
	P	L	H
$E_{\Delta T}$	NL	L	
	PS		VL

4. Results of Temperature Control

Our preceding work [12] showed that a fuzzy logic controller that included the difference between the air temperature and the room setpoint, its derivative, and its integral, resulted in a controller that performed the best at keeping room temperatures close to their setpoints. This work, however, focuses on examining controller robustness, by conducting two experiments to assess its ability to respond to changes in temperature setpoints: (1) once within a 60 min testing period, and (2) twice within a 90 min testing period.

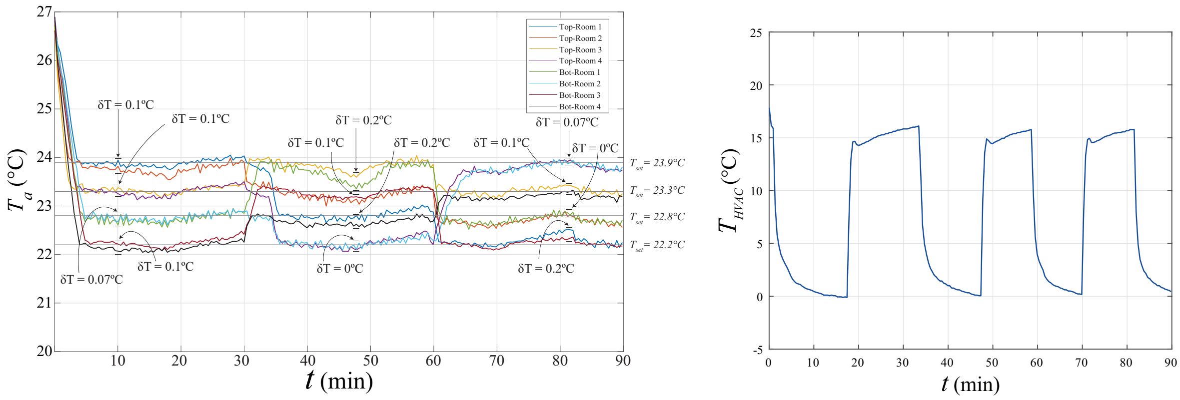


(a) Controller response to different setpoints. (b) Air temperature from HVAC system.

Figure 4. Time dependent air temperatures in building for experiment 1.

The first experiment was conducted over a period of 60 min, in which four setpoint air temperatures (each assigned to two rooms), within the range of 22.2°C to 23.9°C, were employed. Firstly, for a period of $t \in [0, 30]$ min, top rooms 1 and 2 were set to 23.9°C, top rooms 3 and 4 were set to 23.3°C, bottom rooms 1 and 2 were set to 22.8°C, and both bottom rooms 3 and 4 were set to 22.2°C. Then, at $t = 30$ min, the code was programmed to change the setpoints to the following values: Top Room 3 and Bottom Room 1 to $T_{set} = 23.9$°C; Top Room 2 and Bottom Room 3 to $T_{set} = 23.3$°C, Top Room 1 and Bottom Room 4 to $T_{set} = 22.8$°C, and both Top Room 4 and Bottom Room 2 changed to $T_{set} = 22.2$°C. The results are presented in Fig. 4(a) for the time evolution of room temperatures and Fig. 4(b) for the trend of cold air temperature supplied by the HVAC unit. Here, δT, is used to denote the temperature difference between each pair of rooms for a given setpoint. From Fig. 4(a), it is evident that the controller successfully achieves the desired room temperature, reaching the respective setpoints within 5 min (from an initial value of 26.7°C), and maintaining them to within ±0.3°C of the setpoint values. This figure also shows that δT for each pair of rooms is kept within 0.2°C of each other.

Once the setpoints change at $t = 30$ min, Fig. 4(a) shows that only about 2 min were needed for the rooms to reach their new temperatures (Bottom Room 1 being the exception, as it took 10 min to increase 1.1°C). The figure also illustrates the appearance of some spikes in the T_a-curve for Top Room 4 and Bottom Room 2 of magnitudes +0.2°C at $t = 40$ min, and +0.3°C at $t = 54$ min. On a closer look, it is seen that these spikes correlate with the changes in the temperature of cold air delivered by the HVAC device, as shown in Fig. 4(b). The similarities between the room- and HVAC-air temperatures become quite evident when comparing Figs. 4(a) and 4(b). For instance, the 'dents' in room temperatures at $t = 14$, 33, 45, and 58 min, all agree with the dips in temperature curves of Fig. 4(b). However, for all cases it is observed that the controller took immediate action and either opened or closed the dampers, leading to either an increase or decrease in the air-flow until the setpoint temperatures were met.



(a) Controller response to sudden closure of two dampers.

(b) Air temperature from HVAC system.

Figure 5. Time dependent air temperatures in building for experiment 2.

The second experiment was conducted over a period of 90 minutes, by adding a third change in the temperature setpoints of all rooms to those already used in experiment 1. Thus, for the period of $t \in [0, 60]$ min, the setpoints are those utilized during the first experiment. For the third setpoint change, during $t \in [60, 90]$ min, these were set as follows: Top Room 4 and Bottom Room 2 to $T_{set} = 23.9$°C, Top Room 3 and Bottom Room 4 to $T_{set} = 23.3$°C, Top Room 2 and Bottom Room 1 to $T_{set} = 22.8$°C, and both Top Room 1 and Bottom Room 3 to $T_{set} = 22.2$°C. The results are shown in Fig. 5, with room temperatures pictured in Fig. 5(a) and cold HVAC air in Fig. 5(b). From Fig. 5(a), it is seen that it only takes 4 min for all rooms to reach their setpoints, with δT being kept within 0 to 0.2°C. For this new experiment, it is apparent - again - that the controller is capable of keeping the room temperatures close to the setpoints, the exception being the two major drops of −0.4°C for Top Room 2, at $t = 47.7$ min, and of −0.5°C for Bottom Room 1 at $T_{set} = 22.8$°C. It is to note that: (a) in all the curves, it takes longer for the temperature to rise than to decrease to a specific setpoint (due to limited lightbulb power supply), and (b) the 'dips' in $T_a(t)$, coincide with those of the HVAC air supply (cf. Fig. 5(b)) which, some cases, amounts to a 15°C change. In all cases, however, the controller is able to maintain the room temperatures very close to the corresponding setpoints.

As indicated above, for $t \in [60, 90]$ min, the controller managed to keep the temperatures close to their respective setpoints and, as expected, it took longer for Top Room 4 and Bottom

Room 2 to reach $T_{set} = 23.9°C$ from an initial value of $T_a = 22.2°C$. Likewise, a temperature undershoot is seen for both Top Room 2 and Bottom Room 1 at $t = 70$ min, which again parallels the temperature drop of the HVAC air supply, shown in Fig. 5(b). However, the controller acted accordingly by closing the dampers to these rooms, thus allowing their temperatures to increase and reach $T_{set} = 22.8°C$. As previously discussed, from Fig. 5(a) and 5(b), it is easy to see that there is a link between the temperatures in the rooms and the cold air delivered by the HVAC. The 'dips' in the room temperatures of Fig. 5(a) agree with the sudden drops seen in Fig. 5(b) at $t = 17$, 47, 70, and at 90 min. Similarly to experiment one, the controller opened or closed the dampers accordingly until the temperatures in the corresponding rooms met their setpoints.

5. Conclusions

Temperature control of multi-room buildings is essential to both ensure thermal comfort of occupants and to reduce energy waste. However typical control laws lack robustness and may not be suitable for these applications. Previously we have shown that fuzzy control of buildings are viable [12]. In this study, we have expanded on this idea to test the robustness of fuzzy controllers for buildings, and assessed their ability to deal with internal disturbances, like (a) changes in temperature setpoints, and (b) changes in the operation of the system, and external disturbances, like changes in cold air temperature supplied by the external HVAC unit.

The results from these tests demonstrate that the fuzzy controllers are robust since they are able to maintain the room temperatures very close to the corresponding setpoints, despite changes in these or sudden closure of the air supply. However, details in the trends in room temperature clearly show that the external HVAC unit places a crucial role in the control process of the building testbed, since its operation, which seems to be oscillatory in nature, provides external disturbances which were unaccounted during the development of the controller. However, even under these extreme conditions, the results demonstrate that fuzzy controller is able to regulate, within the design limits of the system, the temperature of all rooms.

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