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FUZZY CONTROLLER RESPONSE TO INTERNAL AND EXTERNAL DISTURBANCES IN A MULTI-ROOM BUILDING TESTBED

A. Saguilan[1] A. Pacheco-Vega[1,*]

[1]California State University–Los Angeles, Los Angeles, CA, 90032, USA

ABSTRACT

We extend previous work on the effective strategies, via fuzzy logic, for thermal control of a multi-room sub-scaled building testbed. Here the focus is placed on the robustness of the fuzzy controller to deal with internal and external disturbances, as well as with multiple setpoint temperatures occurring within the same experiment. The objective is to maintain a specific temperature in the rooms of the building. The controller is built on time-dependent information about the difference between the setpoint and the actual room temperatures, their derivative, and the cumulative integral of it. The fuzzy sets are built with triangular membership functions; the rules are built from experiments. A Mamdani inference method is used to defuzzify the outputs providing a crisp value to the actuators. The control variables are average temperatures in the rooms while the air flow rates are the ones being adjusted. The system consists of eight rooms, distributed on two floors, with a cooling unit providing cold air to the system, and 40W light bulbs that act as heat sources in each room. Two T-type thermocouples are placed in each room to gather temperature data, and eight dampers are used to deliver the airflow from the cooling unit. Temperature readings and control actions are performed via LabVIEW, and MATLAB is used to implement the fuzzy controller, while experiments are conducted to assess its performance. Results demonstrate that the fuzzy control strategy can effectively provide thermal control of the testbed under either type of disturbance or different changes in setpoints.

KEY WORDS: Fuzzy logic; Multi-room building; Experiments; Thermal control

1. INTRODUCTION

During the last 200 years, the use of fossil fuels, as a source of energy in many important application areas, has been key for the industrialization of world society. At the same time, pollutants resulting from energy conversion processes based on fossil fuels have substantially contributed to global climate change [11]. To reverse this trend, it is thus necessary to increase the efficiency of both the generation and use of energy in urban-related sectors. An important example is that of the residential and commercial building sector, which uses nearly 40% of the global energy consumption [5], and it is estimated to increase by 48% by 2040 [6].

The effective design and control of heating and cooling processes and associated systems in buildings, which are essential for human comfort, are important if a goal is to use and conserve energy in an effective manner. This is, however, not a simple task because of system complexity either due the nature of the phenomena, the interaction between the building and its surroundings, and the large number of parameters involved, all of which prevent using accurate and compact models [7, 22]. For control purposes in multi-room buildings, for example, models based on PDEs are very difficult to solve in real time, so that the thermal engineer has to rely on non-model-based controllers, being the PID scheme the *go-to* type of controller because of its straightforward implementation and tuning [10]. However, lack of robustness and constant need for re-tuning

*Corresponding A. Pacheco-Vega: apacheco@calstatela.edu

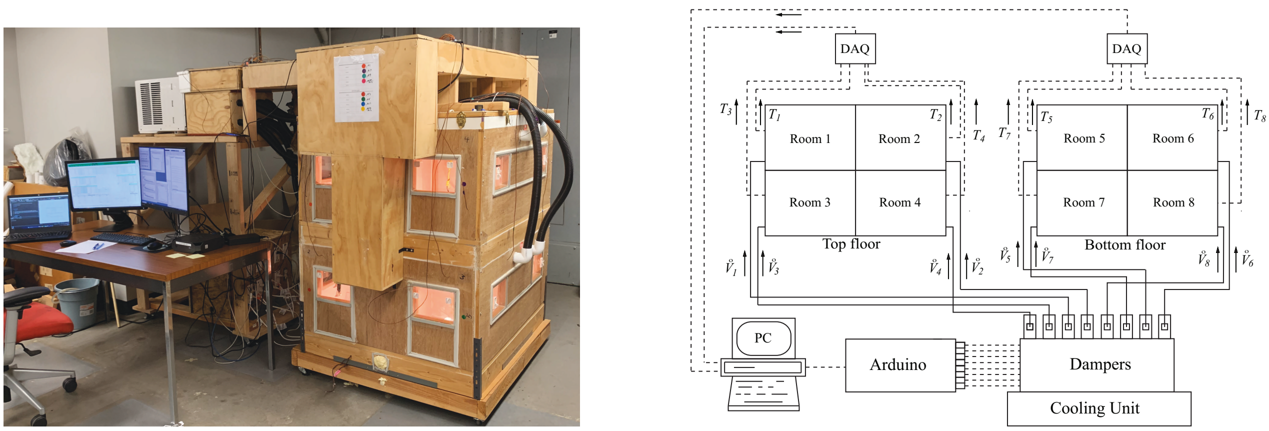
are among the main drawbacks of the PID [8], which potentially, degrade controller performance and decrease thermal comfort [12]. Thence, alternative control strategies for thermal control in buildings are necessary.

The use of control schemes based on the fuzzy logic technique [25], has gained attention in the field of thermal engineering due to their ability to apply human experience to perform the control actions. The capability of fuzzy logic to use linguistic variables and expert-based rules to describe the behavior of complex systems has shown to be effective in many areas of application. Examples include the thermal control of heat exchangers [17, 21], heat pumps [24], and photovoltaic systems [23], etc. However, only a handful of studies have been reported for the case of thermal control of buildings, either using data derived numerically [1, 9], or by combining fuzzy logic with other soft computing methods [4, 15]. Recently, Baltazar et al. [3] reported advances in fuzzy control of a building experimental facility, in which it was shown that accuracy of the controller is linked to the amount of information about the system provided to it.

In this study we expand upon our previous work on the thermal control of a multi-room building testbed, based on the fuzzy logic technique [3], with a focus on the robustness of the controller to deal with internal and external disturbances. To this end, a brief description of the facility is presented first, followed by a general introduction of the fuzzy logic methodology. A brief account about the fuzzy control scheme used to regulate the room temperatures in the building is given next. Finally, the results on the response from the fuzzy controller to either internal or external disturbances, demonstrate that the fuzzy control strategy can effectively achieve the corresponding setpoint. However, there is a limit beyond which the system becomes uncontrollable.

2. EXPERIMENTAL TESTBED

The experiments in this study are carried out in a sub-scaled building testbed, illustrated in Fig. 1. The facility, with dimensions: 1.2 m by 0.92 m by 1.1 m in height, has eight rooms of the same size that are distributed on two floors. Wood is the material used for the structure of the building while the interior walls are build with drywall and R-19 insulation. A set of 40 W incandescent light bulbs provide the heating process inside the building, while the cooling process is carried out via an external HVAC unit. Cold airflow from the HVAC is delivered to each of the rooms through a set of ducts, each connected to the supply vents. Average air temperatures inside each of the rooms are measured from two type-T thermocouples. The air flow rate to be delivered to each room can be regulated by a set of eight dampers that are operated by the fuzzy controller via an Arduino microcontroller that is connected to a personal computer (PC).



(a) (b)

Fig. 1 Sub-scaled building testbed. (a) Picture and (b) Full schematic.

Temperature data in each of the rooms in the building is collected via two eight-channel data acquisition

(DAQ) boards that are connected on one end to the experimental device and, on the other, to a PC. LabVIEW serves as interface between the testbed and the controller, acquiring temperature readings from the setup and send them to MATLAB, where the fuzzy logic controller generates its output. The desired control action from the controller is then sent to the Arduino microcontroller in order to modify the angle of each damper in the outlet manifold of the cooling unit. The final action is the supply of air flow rate to all the rooms. Temperature readings $T(t)$, of each room, acquired at constant time intervals and stored in the PC for further analysis.

3. OPEN-LOOP SYSTEM DYNAMICS

To develop a robust controller, having a good understanding of the system dynamics without any control action (open loop) is key. Therefore, a 30-minute test, under no control action, was carried out in the facility. The goal of the test (first reported in [2, 3] but included here for completeness), was to study the interaction between the building testbed and the cooling unit (details are in [3]).

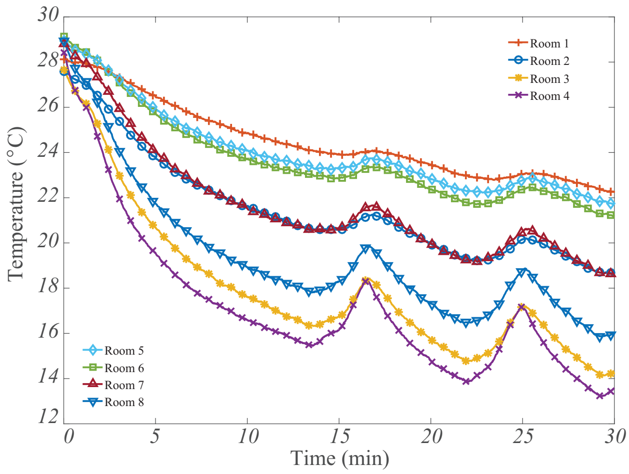


Fig. 2 Building testbed dynamics with fully-open valves.

In the test, the results of which are shown in Fig. 2, the rooms in the building were first heated to an air temperature $T \in [27, 29]$°C, and then cooled for 30 min with all dampers fully opened. From the figure, it can be seen that: (1) uneven delivery of cool air by the dampers connected to the HVAC unit provide a different cooling rate (different slopes); (2) the heat transfer process that takes place in each room shows the typical exponential decay behavior in the average room temperature; and (3) the cyclic operation of the compressor in the HVAC unit enable peak values of average air temperature at $t = 17$ min and $t = 25$ min. Note that this variation in air temperature acts as an additional disturbance (external) to the fuzzy controller.

4. FUZZY-BASED CONTROL

4.1 Background

Fuzzy logic (FL) is a soft computing methodology that uses linguistic variables and ‘expert’-based rules to describe the behavior of complex systems. A main characteristic of the technique is its ability to handle vagueness and imprecision in the data to solve a particular problem [20]. As a result, since its inception in the 1960s, fuzzy logic has been applied successfully to a number of engineering applications, in particular in the area of system and process control [16]–[18]. In these applications, the description of the behavior of a given engineering device is carried out by first defining its inputs and outputs in terms of linguistic variables (e.g., ‘small’, ‘medium’, or ‘big’), and then by quantifying them using fuzzy sets, which follow are associated to a specific rule-base composed of if-then statements. The concept of fuzzy sets relies on a continuous scale of membership of an element belonging to a specific set (e.g., either fully belongs, partially belongs or does not belong), and provides a generalization of the concept of a strict binary crisp set, where an element can either belong to the set or does not belong in it [25, 26]. In the context of air room temperature in a building, for example, if one uses crisp sets, then such temperature T_f “is” either hot or it “is not”. On the other hand, if we use fuzzy sets, then a the air temperature T_f, can be described anywhere in between ‘very cold’, ‘cold’, ‘warm’, ‘hot’, or ‘very hot’. These representations are defined mathematically as

$$\text{Membership in a crisp set:} \qquad \mu_A(T_f) = \begin{cases} 1, & T_f \in A \\ 0, & T_f \notin A \end{cases} \tag{1}$$

$$\text{Membership in a fuzzy set:} \qquad \mu_A(T_f) \in [0,1] \tag{2}$$

$$\text{Fuzzy sets for air temperature:} \qquad A(T_f) = \sum_i \frac{\mu_A(T_{f,i})}{T_{f,i}} \tag{3}$$

for variables defined in terms of crisp sets or fuzzy sets, respectively. In Eqs. (2) and (3), μ_A is the membership function for the i-th fuzzy air temperature set. After a so-called fuzzification process, in which 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 – via output membership functions – which then is mapped back (by a so-called defuzzification process), into a crisp value. In the present work, this last step is done via an inference system developed by Mamdani [14]. Additional information about its mathematical background and applications can be found in several books and monograms, including those of Passino and Yurkovich [18], and Chen and Pham [19].

4.2 Fuzzy Controller

In the context of thermal control for the building testbed under analysis, the variables involved are the air flow rates, $\dot{\mathcal{V}}$, and room temperatures, $T(t)$. In the fuzzy-based strategy, both will be represented as linguistic variables to describe their state. Thus, following recent studies by Baltazar et al. [2, 3], the overall control system is composed of eight single-input single-output (SISO) control loops, each associated to a fuzzy controller for each room. In each controller, air flow rate $\dot{\mathcal{V}}$, delivered into each of the rooms, is the control input, while air temperature $T(t)$, is the system output. This closed-loop system is schematically shown in Fig. 3.

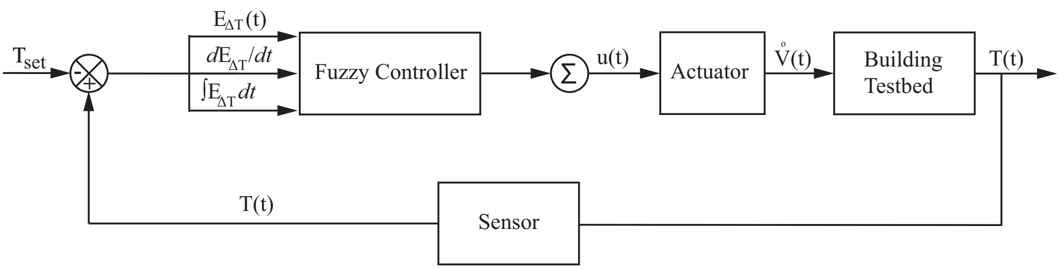
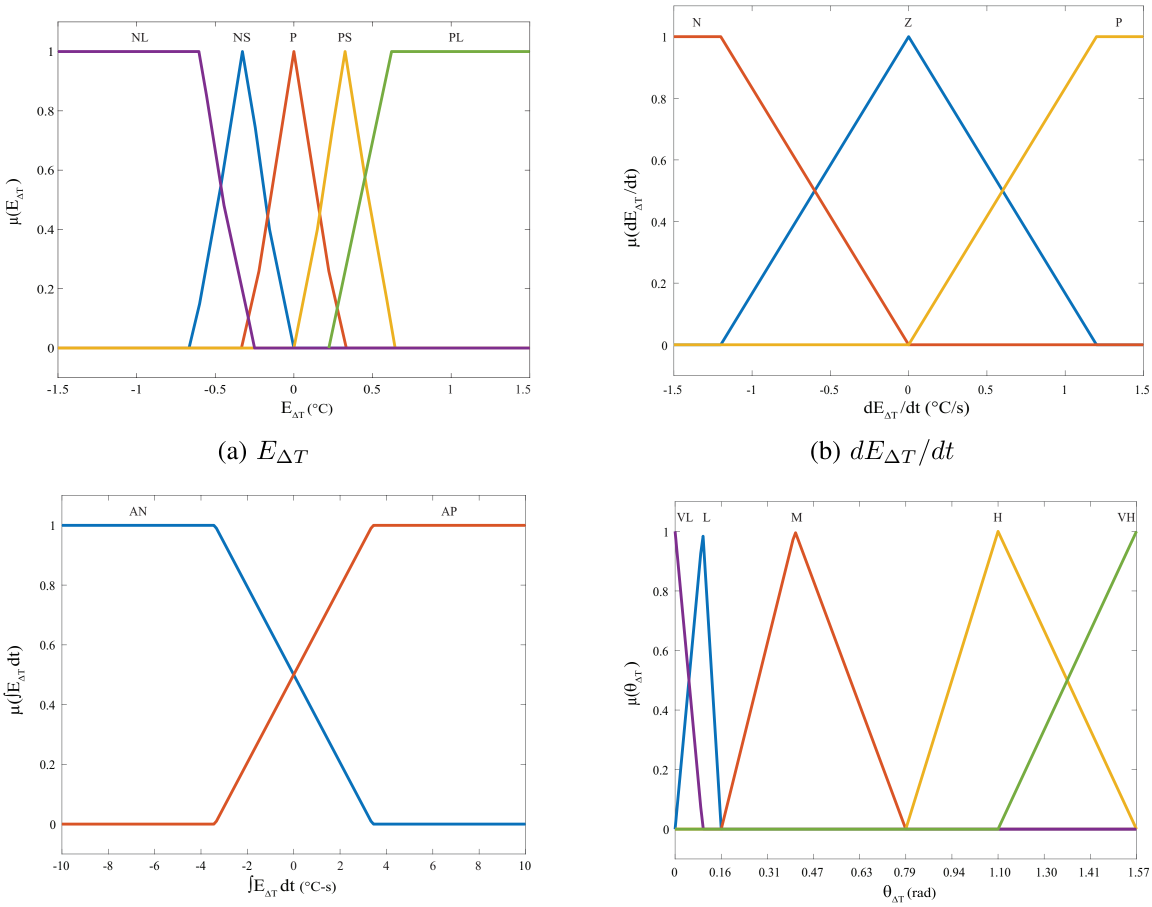


Fig. 3 Schematic of closed-loop fuzzy control.

In addition, following the work of Pacheco-Vega et al. [17] and Ruiz-Mercado et al. [21], all the controllers were built with information about the error between the setpoint, T_{set}, and the actual room temperatures, $T(t)$; i.e., $E_{\Delta T} = T_{set} - T(t)$, its difference over time $dE_{\Delta T}/dt$, and the integral of such error over a period of time, $\int E_{\Delta T}dt$, all linearly combined. On the other hand, Fig. 4 shows the membership functions and corresponding fuzzy sets for the fuzzy controller. From the figure, it is possible to observe that the fuzzy sets for $E_{\Delta T}$ are composed of 2 trapezoidal and 3 triangular membership functions in the range [-10, 10]°C; those for $dE_{\Delta T}/dt$ are composed of two trapezoidal and one triangular membership functions in the range [-1.5, 1.5]°C/s, and the fuzzy sets for $\int E_{\Delta T}dt$ contains two trapezoidal membership functions in the range [-10, 10]°C-s. In addition, the corresponding fuzzy sets for the angle $\theta_{\Delta T}$ are built with 5 triangular membership functions in the range [0, 1.57] rad, with $\theta_{\Delta T} = 0$ radians being a fully-closed damper (angle of 0°), and $\theta_{\Delta T} = 1.57$ radians being a fully-open damper (angle of 90°).



(a) $E_{\Delta T}$ (b) $dE_{\Delta T}/dt$

(c) $\int E_{\Delta T} dt$ (d) $\theta_{\Delta T}$

Fig. 4 Fuzzy sets and membership functions for fuzzy controller.

Finally, the set of inference rules are presented in Tables 1 and 2 where, in agreement with Fig. 4, 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 values for $dE_{\Delta T}/dt$, are 'N', negative, 'Z', zero, and 'P', positive, with 'NR' being a no-rule. For $\int E_{\Delta T} dt$ the corresponding values of the fuzzy sets are 'NL', negative large, 'AN', always negative, and 'AP', as always positive. The well-known Mamdani inference method [13] is used to defuzzify the outputs in order to generate a crisp value to the actuators (dampers) to provide the appropriate air flow rates to the rooms.

Table 1 Decision matrix 1 for $\theta_{\Delta T}$ involving $E_{\Delta T}$ and $dE_{\Delta T}/dt$.

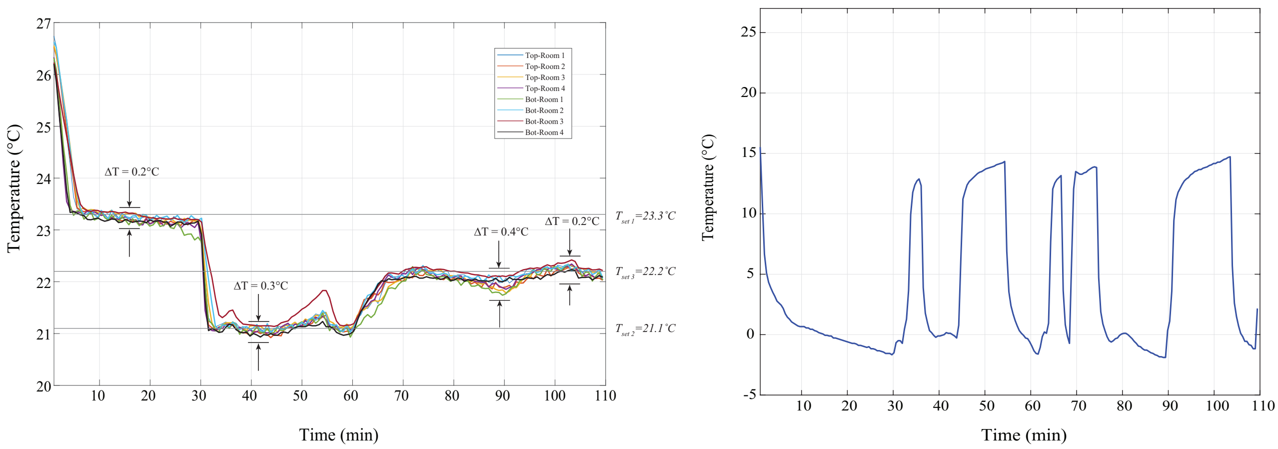
$\theta_{\Delta T}$		$E_{\Delta T}$				
	↘	NL	NS	Z	PS	PL
$dE_{\Delta T}/dt$	N		VL	L		
	Z	VL	VL	L	L	VH
	P		M	H	H	
	NR	VL	L	M	H	VH

Table 2 Decision matrix 2 for $\theta_{\Delta T}$ involving $E_{\Delta T}$, $dE_{\Delta T}/dt$ and $\int E_{\Delta T} dt$.

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

5. RESULTS OF TEMPERATURE CONTROL

Our previous work [3] has showed that the performance of the fuzzy logic controller which included information about the difference between setpoint and room temperature, along with its corresponding derivative and integral, performed the best at keeping the temperatures in the rooms closer to their setpoints. Here, we are interested in investigating its robustness by conducting two comprehensive experiments to assess its ability to (1) respond to both multiple changes in the temperature setpoint, and (2) the second a sudden change in cold air supply, both of which we consider them to be internal disturbances, as discussed next.



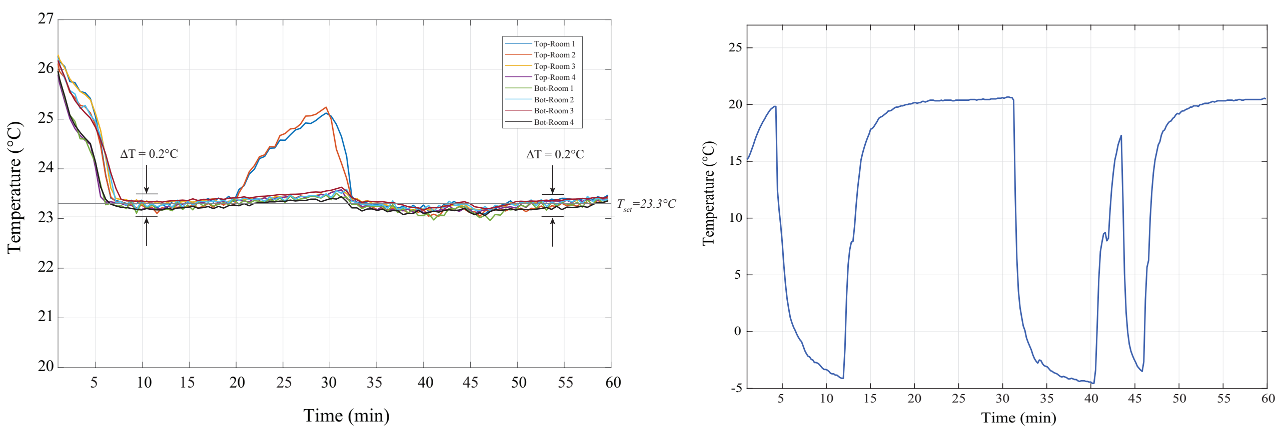
(a) Controller response to different setpoints. (b) Air temperature from HVAC system.

Fig. 5 Time evolution of room temperatures in response to the fuzzy controller for experiment 1.

The first experiment was conducted over a 110 minute time span, in which the controller was subjected to three consecutive sets of temperature setpoints for all rooms in the testbed. The first set was fixed at $T_{set\ 1} = 23.3$°C for the first 30 minutes, then changed to $T_{set\ 2} = 21.1$°C for the second time frame of 30 min, and finally to $T_{set\ 3} = 22.2$°C from the minute 60 to 110 minutes. The corresponding results from the experiment are shown in Fig. 5. From Fig. 5(a), which shows the history of room temperatures in response to the fuzzy controller, it is observed that, within a 6 minute time frame, the controller was able to bring the temperature of all rooms to 23.3°C (from an initial value of 26.7°C), and then to maintain them within 1°C of the setpoint for about 10 minutes (noting that the temperatures of all the rooms were kept to within ± 0.2°C of each other). At $t = 30$ min, the setpoint was decreased to $T_{set\ 2} = 21.1$°C, with the controller being able to successfully reach, within 1 minute, all the rooms to within ± 0.2°C of the setpoint and ± 0.3°C of each other for most of the 30 minute period. Finally, at $t = 60$ min, an increase in temperature setpoint to $T_{set\ 3} = 22.2$°C. The response from the controller was to close all dampers and allow the light bulbs to increase room temperatures. This process took 10 minutes due to the relatively-low power of the light bulbs used. It is seen that, for the remaining of the test, the fuzzy controller was able to maintain the room temperatures to within 0.3°C of the setpoint, and roughly to ± 0.3°C of each other.

It is to note that, though the fuzzy controller is able to reach and maintain the rooms at the different setpoints, there is some variability in the values and trends of room temperatures. For instance, from Fig. 5(a), one can see that: (1) around the 16-minute mark, a small but gradual decline in air temperature below the setpoint, by about 0.3°C for seven rooms, and 0.5°C for Bottom Room 1, occurs; (2) at $t = 36$ min, a slight temperature increase, followed by a larger one at $t = 54$ min, arises before the controller attempts to reach the new setpoint; and (3) a small dent with maximum temperature change of 0.5°C, at $t = 90$, followed by a small bump of 0.2°C at $t = 103$ min, are present before the experiment is concluded. These trends seem to be in line with the changes in the temperature of the cold air supplied by the HVAC to the testbed, which are shown in Fig. 5(b). For instance, in agreement - respectively - with the results above, (1) the downward slope of the cooling air in Fig. 5(b), is proportional to the gradual decline in room temperature during the first 30 min of the experiment, though with a change in cold-air temperature of 17°C, which the fuzzy controller attempts to handle by adjusting the angle of the dampers. For the increases in room temperature of (2), at $t = 36$ min and $t = 54$ min, are reflected in the corresponding increase in cold air temperature supplied by the HVAC, which again are much larger (close to 15°C) than those of the room temperatures in the building testbed, showing that the controller promptly responds to the disturbance and readjusts its output. A similar situation occurs for the 'dent' at $t = 90$ and the 'bump' at $t = 103$ min in room temperatures of Fig. 5(a), which correspond to the substantial decrease of up to 15°C in the supply air temperature for the period of $t \in [80, 90]$ min, and its subsequent increase for the period of $t \in [90, 105]$ min illustrated in Fig. 5(b). These results demonstrate that the fuzzy controller has the ability to adjust to the unforeseen external conditions of the cooling device, to maintain the room temperature of the rooms within 1°C, which is the uncertainty in the readings from the T-type thermocouples. Some outlier results, like the air temperature of Bottom Room 3 in Fig. 5(a), jumps an additional 0.4°C at $t = 54$ min, likely due to the damper momentarily scraping the side of the pipe, something that the controller cannot regulate.

The second experiment was conducted over a period of 60 minutes, in which a setpoint temperature of 23.3°C was set first, and a subsequent internal disturbance in the form of damping closure for two rooms was applied. The results are shown in Fig. 6, with the time evolution of room temperature being illustrated in Fig. 6(a) and the cold air supply from the HVAC system being shown in Fig. 6(b). From Fig. 6 it can be seen that the fuzzy controller is able to take, within 6 minutes, the air temperature of all the rooms to within 0.2°C of each other, to the appropriate setpoint. Once the building system has reached stable conditions, at $t = 20$ min the dampers for Top Room 1 and Top Room 2, which enable supplying cold air to the rooms, are closed for 10 minutes and then reopened. The corresponding result is the increase in air temperature of both rooms to about 25.1°C. However, it is seen that after the dampers are reopened, the controller is able to quickly perform the control actions, leading to the decrease in the air temperatures of both rooms toward the setpoint. It is important to note that during the time frame in which the two dampers remained closed, the fuzzy controller was able to maintain the air temperature of the remaining six rooms at the corresponding setpoint. These results are indicative of the robustness of the fuzzy controller to handle these types of disturbances. Finally, as it was previously discussed, there is a link between the behavior of the HVAC unit and that of the room temperature of the building, as shown in Fig. 6(b) as trends of the temperature evolution for all the rooms, as the crests and valleys in the temperature history coincide with the sudden changes in cold air temperature supplied to the building by the HVAC. However it is evident that the fuzzy controller is able to maintain all room temperatures to within ±0.1°C of the setpoint.



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

(b) Air temperature from HVAC system.

Fig. 6 Time evolution of room temperatures in response to the fuzzy controller for experiment 2.

6. CONCLUSIONS

Temperature control of multi-room commercial and residential buildings is essential to ensure thermal comfort of occupants and to reduce energy usage. However control laws commonly used lack robustness and therefore may not be suitable strategies for thermal control in buildings. In previous work [2, 3], we have shown that controllers based on fuzzy logic are a viable alternative since they rely on information from human experience on how a system should be controlled. In this work, we have expanded on this idea to test the robustness of a fuzzy controller that is built with information about room temperature error, its derivative and its integral, and assessed its ability to deal with internal disturbances, like (1) multiple changes in temperature setpoint, and (2) changes in the operation of the system, and external disturbances, e.g., changes in temperature of cold air supplied by the external HVAC unit.

The results from these tests showed that the fuzzy controller is very robust as it was able to maintain the temperatures in the rooms very close to the corresponding setpoints, despite changes in the setpoints or sudden closure of the air supply dampers. 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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NOMENCLATURE

$E_{\Delta T}$	temperature error	(°C)	T	room air temperature	(°C)
$dE_{\Delta T}/dt$	derivative of error	(°C/s)	T_{set}	setpoint air temperature	(°C)
$\int E_{\Delta T}$	integral of error	(°C-s)	t	time	(s)
$\theta_{\Delta T}$	output damper angle	(radians)	$\dot{\mathcal{V}}$	volumetric flowrate	(m^3/s)

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