

The Use of Arduino and PID Control Approach for the Experimental Setup of HVAC Temperature Testing

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Abstract—The experimental setup of HVAC testing requires easy but accurate instrumentation, and recent analyses focus on the control based on the mean radiant temperature in order to better perform respect to the users satisfaction. Indeed, the research contribution of this work is the use of Arduino to develop a PID control for an electric heater. As a main feature, this control system can operate by maintaining the set-point on the air temperature or on the mean radiant temperature of the environment where it is placed. The paper describes the design and development of the PID control, as well as the testing of the control system applied to an electric heater, to heat a room in a laboratory in Bologna (Italy). In an Appendix the Matlab script employed to store data on the local pc and to send data to Google Sheets is reported, together with the Google script code employed to write the data from Matlab to the online sheet. As result, the developed PID is accurate in maintaining the required set-point temperature, with minimal deviations from the set-point, in the interval ± 0.2 K.

Keywords—Arduino; PID Control; Experimental Setup; HVAC Testing; Matlab; Google Script; Air Temperature; Mean Radiant Temperature.

I. INTRODUCTION

In design and validation of heating systems, temperature measurements and HVAC control are recurrent activities. In some cases, experimental data are used to validate or cross-check numerical solutions [1] [2]. Applications involve the air temperature or, in some cases, the mean radiant temperature [3]. Concerning the control of the mean radiant temperature in an experimental setup, Aparicio et al. in [4] describe how to construct a globe temperature sensor and detail experiments demonstrating the feasibility of using a black globe thermometer with a 40 mm diameter. Obando Vega et al., in [5], employed a microcontroller for determining mean radiant temperature using globe thermometers. More specifically, they analysed the temperature values obtained using 18 different low-cost black-globe thermometers. Notably, they found that for indoor applications the best results were achieved with metallic globe thermometers with a 67 mm diameter globe, and the DS18B20 digital temperature sensor as the transducer for the controller.

The design of control strategies, for dynamic systems or experimental setup, is necessary in many applications in

science and engineering. In the recent literature, particular attention is paid to the use of model predictive controllers to account for weather forecasting data [6], neural network control solutions [7], genetic algorithms [8][9][10], as well as control valves [11].

Theoretical approaches are available in the literature [12], and a review is analysed by Borase et al [13]. The integration of PID control with Arduino [14] is analysed by Bista in [15]. In the literature, the main applications regard robotics [16] or DC motors [17][18][19][20][21].

Concerning HVAC applications, a pivotal application of PID controls is related to monitoring not only the temperature but also the carbon dioxide in buildings. During the Covid-19 pandemic period [22], to have better air quality inside people-occupied spaces, a great number of air exchange rates are required [23][24][25]. Implementing advanced ventilation technologies, such as demand-controlled ventilation, helps adjust airflow based on real-time CO2 measurements. This leads to an increase in energy consumption, especially those that have discontinuous presences during the day, such as schools [26], conference rooms, and hospitals [27]. Employing intelligent sensors and automated systems for CO2 control creates a healthier environment by preventing the buildup of pollutants and supporting a more sustainable and comfortable indoor space. The PID control is well known for its effectiveness in ensuring a stable indoor temperature while minimizing energy consumption [28][29][30]. Among practical applications for experimental setup, the use of Arduino controllers [14] has been recently investigated by Russi et al. [31] for an application related to comfort indexes.

The Arduino board is well suited for the design of small control systems in several application fields, such as water quality and level control [32][33], watering systems [34], liquid density meters [35], audiometers [36], environmental light and temperature control systems [37][38], chemical laboratory shakers [39], and ultrasonic distance sensing systems [40].

Moreover, in [41] the Arduino control system is integrated with Arduino development environment (IDE) software to write the program code, deserving attention also for its possible use for students applications. In [41], Daoud



reports the block based coding. However, thinking to a possible student application easy tools such as Google script or Google Sheets to collect the data can be used. This choice goes in the direction of construction of a simple and economic measurement and control station, suitable for remote control and with a view to energy saving and monitoring environmental parameters.

To sum up, although the use of Arduino and PID control approach has already been investigated, displaying a good performance, we need to observe more the implementation, with special attention to inhouse hardware solutions, such as a circuit for controlling the TRIAC module, and software solutions, such as the script for data recording.

In this framework, the research contribution is twofold. First, the design of a PID controller for an electric heater using an Arduino controller [14]. The peculiar feature of this control system is that the controller can set the target temperature based either on the air temperature or on the one to measure the mean radiant temperature using a globe-thermometer. As is well known, measuring both air temperature and globe thermometer temperature is essential for comprehensive environmental quality assessment, offering insights into thermal comfort, energy efficiency, and overall well-being. Additionally, the PID controller is complemented by instruments for measuring the current and voltage, in order to determine the power delivered to the electric heater; the results obtained from these instruments are presented and discussed, showing that the developed PID is accurate in maintaining the required set-point temperature.

II. MATERIALS AND METHODS

In this chapter the main equipment and the setting of the analyses performed will be presented.

A. Hardware Architecture

The measurement system includes the use of 2 NTC (Negative Temperature Coefficient) thermistors of 10 k Ω for measuring the air temperature and the mean radiant temperature. In detail, to measure the mean radiant temperature, according to the UNI EN ISO 7726:2001 standard [42] one NTC Thermistor is positioned inside a dark hollow copper sphere with a diameter of 150 mm. Other components of the acquisition systems are a voltage sensor (model ZMPT101B, manufacturer ANGEER) and an electric current meter (model SCT013-010, manufacturer HUABAN), shown respectively in Fig. 1(a) and Fig. 1(b).

All the sensors employed have been calibrated in the laboratory in the measurement range in which they are expected to operate. In particular, the NTC Thermistors have been calibrated in the range 18 – 28°C, the voltage sensor in the range 0 – 230V, and the current sensor in the range 0 – 10 A. In detail, the current and voltage sensors have been calibrated employing as reference a Fluke 1735 three-phase power quality logger (accuracy $\pm 1\%$ in the range considered). Moreover, the NTC Thermistors have been calibrated employing a thermostatic bath and as reference a Pt100 RTD (Resistance Temperature Detector) connected to a Wheatstone bridge, leading to an accuracy of ± 0.1 K.

The values obtained from the sensors are read by the Arduino Uno microcontroller. The microcontroller allows to determine the air temperature and mean radiant temperature values through the two NTC thermistors together with the connected electrical load. Moreover, it also includes an ON-OFF control (Fig. 2(a)) and a PID control to vary the electrical power of the connected load. Specifically, the PID control is carried out through a triac, shown in Fig. 2(b), suitable for modulating a load up to 2 kW.

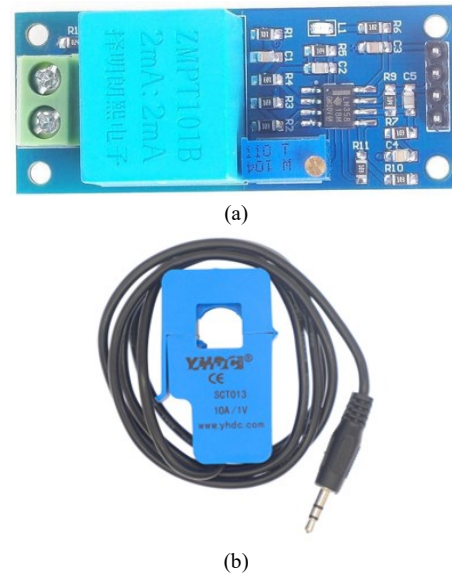


Fig. 1. Voltage sensor ZMPT101B (a) and current sensor SCT013-010 (b)

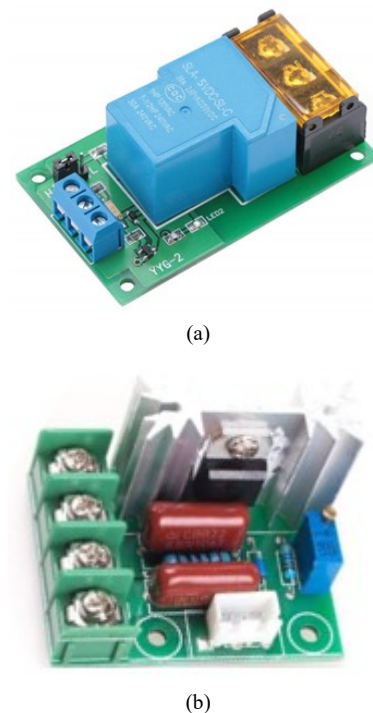


Fig. 2. Relay for ON-OFF control (a) triac for modulating control (b)

B. PID Control Design

Instead of controlling the triac by the native potentiometer, we use the Arduino controller, through relays connected to a series of electrical resistances that can provide a variable resistance at the triac input in the range 0 – 450 k Ω

in steps of 15 k Ω (there are a total of 31 possible resistances in the range). The scheme of the circuit used to control the triac is shown in Fig. 3: each of the five resistances connected in series can be excluded employing 5 different relays (S1 to S5), controlled by Arduino. Thus, 31 different resistance values can be achieved at the triac input.

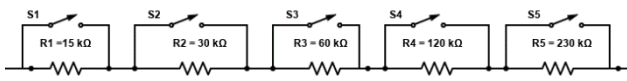


Fig. 3. Circuit for the control of the triac module

The selection of the correct resistance (and ultimately the most appropriate power if an electric heater is connected to the control system) is performed through a PID control developed using the Arduino PID library [43]. The PID control thus acts on the electric power of the heater, setting a control that can be based on either the air temperature or the radiant temperature determined by the NTC Thermistor located in the globe thermometer.

The tuning of the PID has been performed obtaining the PID coefficients for proportional, integral and derivative gain of 25, 5 and 0 respectively. The PID coefficients were determined by trial and error, starting from a unitary value for the proportional, integral, and derivative parts. After various tests, it was observed that the system stability and the best response to temperature variations are achieved with a zero coefficient for the derivative part, 25 for the proportional part, and 5 for the integral part. Moreover, in Fig. 4 the Power input to an electric heater (black line) is reported in response to the signal output of the PID controller (red line). In the figure, the PID control output signal is in this range from 0 to 31. The figure shows a very rapid response capacity.

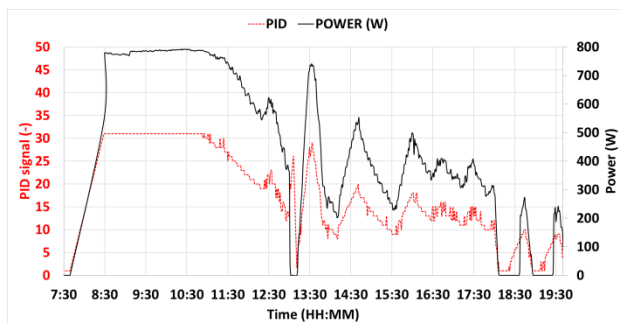


Fig. 4. Power input to an electric heater (black line) in response to the signal output of the PID controller (red line)

C. System Set-Up and Data Acquisition

The scheme of the system set-up is reported in Fig. 5. The microcontroller acquires data from the two thermistors together with data regarding the electric heater, namely on the current and load voltage. The data are processed by the microcontroller in order to set the signal for the PID and the relay. The relay is employed as protection in case of TRIAC malfunction: in fact, it allows to switch off the electric heater whenever the measured temperature is 1 K above the set-point. Moreover, data are collected by means of a Matlab [44] script which records the measured quantities by the microcontroller on a local pc and on a cloud storage service. The code of the Matlab script is reported in the Appendix. In detail, the Matlab script collects data from the

microcontroller via serial port and writes it to a local text file; in addition, through API (Application Programming Interface) requests, it transfers the obtained data (i.e., temperatures, electric power, states of the system components) to an online cloud service.

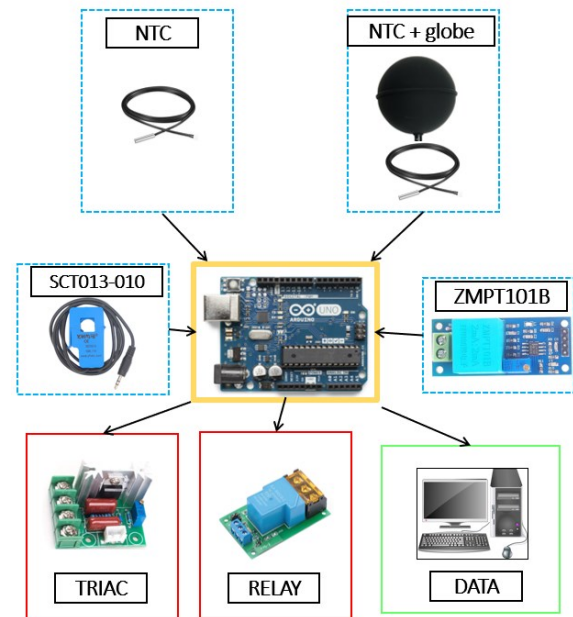


Fig. 5. Schematic view of the system components

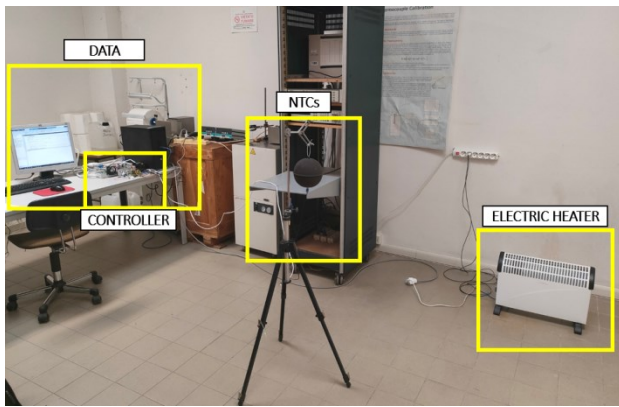
The implemented heating control system has been tested in a laboratory of the Department of Industrial Engineering of University of Bologna. In particular, the control system has been applied to an electric heater (in this case the only heating generation system present in the laboratory, since during the tests the original fan-coil present in the laboratory was switched off), in order to analyze the behavior of the PID when the set-point on the air temperature and mean radiant temperature is imposed respectively.

In Fig. 6(a) the system set-up in the laboratory is shown: the picture displays the electric heater, the data acquisition system, the NTC Thermistors positioning and the microcontroller. In Fig. 6(b) a view of the microcontroller and the hardware connected to Arduino is reported.

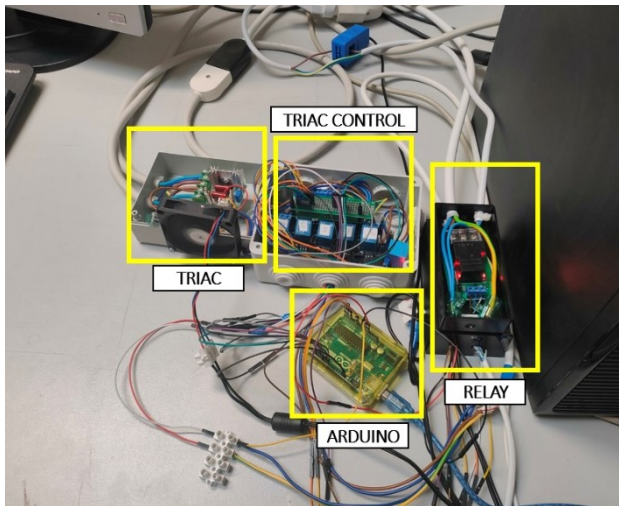
D. Room and Electric Heater Characteristics

The system was tested in a room at the Technical Physics Laboratory of the University of Bologna (Northern Italy, lat. 44° 30' 49.3", long. 11° 19' 8.6"). The layout of the room is shown in Fig. 7, where the positions of the electric heater and the two NTC Thermistors are also indicated.

The building was constructed in the 2000s and has external walls made of concrete and hollow bricks. The room where the measurements were carried out is peculiar, having all its adjoining walls facing other internal environments. In detail, the room has a floor area of approximately 21.5 m², with main dimensions of 5.80 and 3.70 meters. It has two sides facing unheated spaces (a stairwell and a corridor), while the other two sides face other laboratories that are heated only during the occupancy period (generally from 9:00 am to 6:00 pm). Below, there are unheated technical rooms. The room's walls are made of hollow bricks with a total thickness of 16 cm, including the plaster layers.



(a)



(b)

Fig. 6. View of the components in the room (a) and of the hardware connected to the microcontroller (b)

The only external exposure is through 2 skylights present on the roof.

The heater connected to the control system is a commercial electric resistance-based heater, which features a fan to increase convective exchange, and two different internal resistances with power values according to the datasheet of 750 W, respectively. However, during the tests, only the 1250 W resistance was used with the fan turned on, in order to increase the convective heat exchange. The onboard thermostat of the electric heater has been disconnected in order to control the heater only with the Arduino PID control. As reported in Fig. 7, the electric heater is placed in front of the entrance door, 1.10 and 1.20 meters from the room's walls.

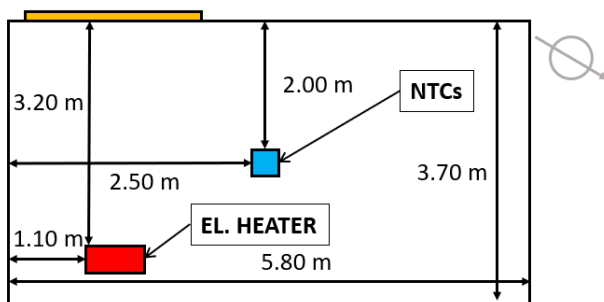


Fig. 7. Layout of the considered room with evidence of the position of the electric heater and the NTC thermistors

The room's native heating system includes a fan-coil unit as the emission terminal, connected to the central heating system of the entire building. This terminal was deactivated during the entire testing period, in order to assess the sole contribution of control through Arduino.

III. RESULTS AND DISCUSSION

In this chapter some experimental analyses performed employing the developed Arduino PID controller will be presented and discussed.

A. Room Temperature Trends with the Heating System Switched Off

The trend of the air and mean radiant temperature within the considered room during a day of the autumn season in Bologna (November 8th) has been acquired. The data have been collected for 24 hours starting from midnight each 1 minute. In Fig. 8 the trends of the temperature alongside are reported together with the outdoor air temperature taken from [45].

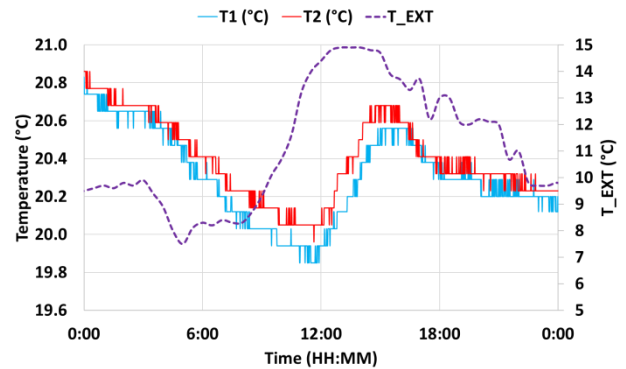


Fig. 8. Air temperature (azure line), radiant temperature (red line), and external air temperature (violet – dotted line on the secondary axe) in absence of electric heater

Fig. 8 shows that during the 24 hours the air temperature and the radiant temperature are very close, with the mean radiant temperature slightly higher than the air temperature. It can be noticed also that the outdoor conditions (i.e. the outdoor air temperature) influence the temperatures inside the room but the influence is very limited, since the temperatures inside range from 19.8°C to 20.9 °C, while the external air temperature varies from 7 to 15°C). This stability is also due to the characteristics of the room considered, which adjoins other heated environments. As is well known, the stability of internal temperature contributes to both energy efficiency [46][47][48][49] and occupant comfort [50][51][52]. Maintaining a stable and comfortable temperature in a building helps reduce the need for frequent adjustments to heating or cooling systems, which in turn can lead to energy savings. Consistent temperature levels also enhance occupant comfort by creating a more pleasant and predictable indoor environment. This stability can contribute to improved overall energy efficiency and a better experience for the occupants.

B. Room Temperature Trends with the Heating System Controlled by the PID

In this section, the results obtained employing the electric heater controlled by the developed PID, as sketched in Fig. 3,

will be presented. The test was conducted during a working afternoon, when the adjacent laboratories were occupied and the heating there was turned on; the average radiant temperature in the analyzed room at the beginning of the test was 20.8°C. The set-point temperature during the test is 22 °C on the mean radiant temperature. In Fig. 9, the temperature trends are reported, showing that the system is able to maintain the set-point temperature on the mean radiant temperature during the entire test (the deviations of the radiant temperature are ± 0.2 K from the set point). The precise temperature control allows for maintaining better comfort inside the building, and improved energy efficiency compared to a typical ON-OFF control system. Furthermore, it is observed that when control is exerted on the mean radiant temperature, the effect is that the air temperature is on average 0.2 °C higher. This result may arise from the heating mode: an electric heater was in fact used, mainly based on convective heat transfer, instead of radiative modes like a radiator.

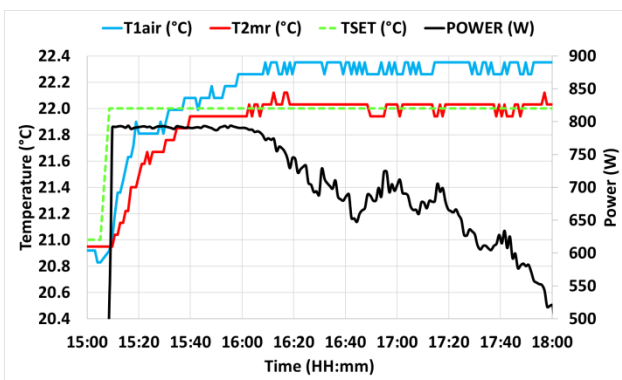


Fig. 9. Air temperature (azure line), radiant temperature (red line), set – point temperature (green dashed line) and power (black line on the secondary axe) when the electric heater is controlled by the PID

IV. CONCLUSIONS

The aim of this work is the development of a PID control using Arduino for an electric heater. The main characteristic of this control system is that it can operate by maintaining the set-point on the air temperature or on the mean radiant temperature of the environment where it is placed. After the design and development, the control system was tested by applying it to an electric heater used to heat a room in a laboratory in Bologna (Italy). As main results, the paper shows that- the developed PID is accurate in maintaining the required set-point temperature, with minimal deviations from the set-point. As is well known, the stability of internal temperature contributes to both energy efficiency and occupant comfort.

Moreover, as interesting result, when the control is on the mean radiant temperature, the air temperature inside the room was found to be 0.2°C higher than the radiant temperature. This result may arise from the heating mode: an electric heater was in fact used, mainly based on convective heat transfer, instead of radiative modes like a radiator.

Future developments will compare the performance of the PID-controlled system with traditional control methods or systems without PID. Concerning the use of the PID control system, future developments will investigate the combination

with other heating systems (radiant panels) and the possible use of the developed system to perform a control considering as controlled variable the comfort indexes (for instance, the PMV [53], Predicted Mean Vote), instead of the temperature. Moreover, future analyses will investigate how the control exerted on the mean radiant temperature influences the thermal comfort or energy consumption.

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APPENDIX

In this section, the two codes employed are reported. Code 1 is a Matlab code, employed to store data on the local pc an to send data to Google Sheets [54], while Code 2, implemented in Google Script, allows the data writing from Matlab to the online sheet.

Code 1

```
function comun1_googlesheet()
% Initial variables
url_endpoint =
'https://script.google.com/macros/s/INSERT_API_KEY_HERE/exec'; %
API HERE
serial_port = 'COM5';
baud_rate = 9600;
filepath = 'results.txt'; % Path to the text file to save results

% Open the serial connection
s = serial(serial_port, 'BaudRate', baud_rate);
fopen(s);

last_save_time = datetime('now'); % Record the last save time

% Check if the file exists and is empty
if ~exist(filepath, 'file') || filesize(filepath) == 0
% If the file doesn't exist or is empty, write the headers
headers = 'Timestamp, T1, T2, POWER, RELAY, PID, T_SET,
T_DB, V_NTC1, R1, R1/R0, V_NTC2, R2, R2/R0, IRMS_AVG,
VRMS_AVG\n';
fileID = fopen(filepath, 'a');
fprintf(fileID, headers);
fclose(fileID);
end

% Infinite loop to read and send data
while true
if s.BytesAvailable
data_str = fscanf(s);

% Display the data_str variable
disp(data_str);

data_array = str2double(strsplit(data_str, ','));

if length(data_array) == 15
% Extract data
temperature1 = data_array(1);
temperature2 = data_array(2);
power = data_array(3);
relayState = data_array(4);
pid = data_array(5);
temperature_set = data_array(6);
```


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