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Optimal PID Control System for Room Temperature Regulation with Classical and Hybrid Gain Scheduling Tuning Methods

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Abstract

Indoor thermal comfort is an important aspect to ensure wellbeing of occupants in a premises. Under the tropical weather in Malaysia, room temperature ranges between 27°C to sweltering 37°C. Appliances such as fan and air conditioning system are commonly used to provide optimal thermal comfort. In this study the Proportional-Integral-Derivative (PID) technology is used to provide comfortable room temperature with optimal air conditioning control. The PID is tuned using three classical PID tuning method; manual tuning (MT), Ziegler Nichols (ZN) and Cohen Coon (CC). and a hybrid gain scheduling (HGSPID). The control parameters are dynamically adjusted based on varying environmental conditions and occupancy patterns. The controllers are tested with three desired room temperature at 17°C, 20°C, and 22°C. The results show that HDSPID has the best performance than the PID controller tuned using classical methods when both settling time and overshoots are considered. The CC tuning provides 0% overshoot for all tested temperatures, but the settling time is longer, while ZN has the same settling time as HGSPID but a high overshoot. MT has the worst performance in both overshoot and settling time.

1. Introduction

In a tropical country such as Malaysia, where the outdoor temperature ranges between 23°C to 38°C [1] and room temperature between 27°C to 37°C [2], there is a growing demand for better thermal comfort in building environments. Comfortable ambient temperature can guarantee physical and mental wellbeing and productivity of the occupants [3], [4], [5], [6]. An uncomfortably warm room is known to induce stress, irritability, sleep disturbances, reduced motivation, decreased mood and enjoyment, and agitation, physically high heat cause increased heart and respiration rate as well as imbalance in electrolytes [7]. Excessive sweating may cause electrolytes imbalance which causes fatigue that reduces productivity. Additionally, maintaining the room at an average temperature is also important to avoid the deterioration of food, medicine, and other items in the room [8].

Modern heating, ventilation, and air conditioning (HVAC) systems have the capability to efficiently control room temperature by cooling, dehumidifying, or even heating. However, the HVAC system is among the highest energy consumer where it is reported to consume up to 38% of total building energy consumption worldwide[9], [10]. Optimal usage of HVAC ensures thermal comfort at optimum cost. Advanced control systems like the proportional, integral, derivative (PID) can be applied to achieve this objective. The controller combined with input from sensors adaptively response to the environmental value sensed so that the room temperature can be maintained at desired value [11].

PID controller is a close loop control system where a desired set point is maintained by adjusting the actuator parameter according to sensor input. In this work, the actuator is the air conditioning which is controlled using temperature sensor input. The PID algorithm is employed to achieve the desired room temperature setpoint. The primary drawback of conventional PID type controllers is lack of self-tuning capabilities. In order to achieve a setpoint, the PID parameters are anticipated to oscillate during various periods of the control process or as the system's dynamics or operating conditions change [12]. There are several classical PID parameters tuning methods, namely, manual tuning (MT) or try and error, Ziegler Nichols (ZN) and Cohen Coon (CC). In this work the temperature control PID is tuned using these classical methods and a proposed hybrid method, where the PID is hybridized with gain scheduling technique. The parameter tuning method that able to improve the settling time and reduce overshooting of the controller is identified. The results show that the hybrid gain scheduling PID (HGSPID) achieved a faster settling time and lesser overshooting compared to other methods.

This paper is organised as follows. Section 2 provides review of previous works, section 3 explains the methodology using the block diagram of the designed room temperature PID control systems. In Section 4 simulation results of the classically tuned PID and HGSPID controller at three different temperatures are presented and discussed. The paper ends with the conclusion and future direction section.

2. Related Work

PID controller has been widely used for temperature control system. A PID controller for a temperature control system is proposed in [13]. The PID controller is tuned using the Ziegler-Nichols method and the characteristics and limitations of different control schemes, such as P, PI, and PID control are also discussed in the work. According to the findings, a proper design and tuning are important to ensure the PID controller to achieve optimal performance in temperature control. Another temperature control system using a PID controller is proposed by Sudhir Ranjan et al. in [14]. The proposed control system is an auto tuned system that provides a safe and efficient cooling mechanism using temperature sensor, voltage regulator, relay switch, LCD display, and push buttons. The system is user-friendly and low-cost, with easy access to its components.

The analysis of mathematical modeling and PID-based temperature control systems is presented in [15]. The study examines transfer of heat within the system and highlights the equations for conductive and convective heat transfer. The concepts of thermal resistance and thermal capacitance are clarified. Next, two tuning methods for the PID controller are presented. The first method is based on the response to a step input, while the second method is based on sustained oscillations. These techniques are used to determine the PID controller's parameters.

Su et al. [16] suggested an advanced fuzzy PID controller by integrating fuzzy logic with the traditional PID control strategy. Using Simulink, a comprehensive simulation analysis was conducted to compare the performance of traditional PID and fuzzy PID temperature control techniques. The simulation results highlighted that the fuzzy PID controller effectively eliminates time delay and stability issues commonly faced in traditional PID-based temperature control systems. Besides, empirical testing confirmed that the fuzzy PID algorithm efficiently regulates server room temperature while reducing cold air intake, hence enhancing energy efficiency. Nevertheless, the research does not explore the adaptability of the fuzzy PID controller in dynamic temperature change, hence limiting its application in dynamic temperature control scenarios.

A further study in [17] examines the optimisation of a PID controller for a temperature control loop in a tank. The research described the development of mathematical models, contrasting theoretical and practical methodologies utilising MATLAB. The construction of the PID controller and its function in temperature regulation are clarified, with the application of a particular strategy for determine PID parameters. The document contains information regarding the system's response and the model output derived from real-time data. The study in [18] examines the application of controllers for regulating the temperature of a demineralised water tank. It evaluates the efficacy of various controllers and provides mathematical models for the system. Experimental evidence validates the models, demonstrating that PID controllers outperform PI controllers in temperature regulation. This study examines tuning approaches for controllers and their implications on system performance.

In recent years, numerous intelligence algorithms have been employed to optimise PID settings. For example, the Particle Swarm Optimisation (PSO) algorithm [19] and the Ant Colony Optimisation algorithm [20]. have been employed to optimise the PID parameters. A deep PID neural network controller's application to a thermal regulatory control problem is covered in [21]. It tackles issues in managing systems characterised by nonlinearity and time delays, suggesting advanced control algorithms for enhanced temperature regulation. The deep PIDNN controller dynamically modifies parameters to improve control performance relative to conventional PID control techniques. This method seeks to efficiently stabilise temperature responses at a defined set point. A study about temperature control systems in a thermal vacuum chamber for the evaluation of spacecraft components is presented in [22]. It presents a control system that integrates a traditional PID controller with a neural network for multi-channel temperature forecasting. A fuzzy self-tuning PID for controlling an incubator's temperature was developed and presented in[23].

Recent research on temperature control systems emphasises multiple applications of temperature controllers. This demonstrates the significance of the PID controller, which is commonly utilised in systems. The use of PID controllers among other techniques for controlling temperatures in ambulances is described in [23]. The regulating of boiler temperature is addressed in [24]. It presents a novel controller and emphasises the significance of accurate controlling temperatures in boilers, as well as the influence of different control techniques on system performance. However, the limitation of conventional PID controllers is in their failure to deliver adequate control performance throughout all stages of the process due to their fixed gain [24]. The PID is typically integrated with other methodologies such as fuzzy logic, neural networks, and optimisation algorithms to attain an enhanced answer. Additional study is required to formulate more efficient control strategies for tackling issues in nonlinear and time-delay systems.

Gain scheduling is known as good robustness and has implemented in the control systems of some applications. A gain-scheduling approach based on the guardian maps theory is introduced by Zhang et al., using the aircraft's generated Linear Parameter Variable (LPV) model as the object. The proposed controller parameter gain-scheduling technique, which utilises guardian maps, circumvents the need to construct the controller at several state points. This strategy reduces the amount of effort, simplifies the design process, and offers meaningful practical benefits. This controller design is capable of satisfying the performance criteria that have been verified in the nonlinear model [25].

Yahagi et al [26] present a design approach for a data-driven gain-scheduled PID controller that takes into account sparsity characteristics without system identification for two different types of nonlinear systems. The results indicate that it is possible to establish a controller with a high level of sparsity without requiring knowledge of the specific features of the controlled object, even when dealing with a significant number of control parameters for the gain scheduler. In short, it was feasible to implement gain-scheduled PID control with minimal computational computation cost and ROM storage space, without the need for trial and error parameter adjustment.

A previous study proposed a PID control approach using integral gain scheduling to address the issue of inadequate control over a superheated steam temperature (SST) system under load variations. The simulation performance validated the efficacy of this approach and demonstrated promising potential for useful applications [27].

Lin et al. introduce a PID [28] algorithm to an ESP12F-based heater table and optimize it for intelligent temperature control. The article concentrates primarily on hardware implementation of the PID algorithm and provides details of its control mechanism. Experimental outcomes show that the optimized PID algorithm enhances temperature control performance with a mean error less than 3% during heating from room temperature to 255°C. However, the paper is missing a comparison with other cutting-edge control techniques such as fuzzy logic or model predictive control that could introduce even greater developments. It fails to also investigate the long-term stability and responsiveness of the system for various operating conditions, which are critical in real-world applications.

The greatest advantage of gain scheduling is that controller parameters can be shifted fast in response to changes in plant dynamics because no additional parameter estimation is necessary [24]. Thus, this study presents the use of HGSPID to enhance the efficiency of current temperature design in PID controller. Indoor thermal comfort temperature in subtropical nations exhibits extremely wide variation, ranging from 15.0 to 32.5 °C, representing the broadest range in comparison with all other climatic zones. On the other hand, tropical nations exhibit a range of 22.0–33.8 °C for comfortable temperature. Field studies in temperate climates depict a comfortable temperature range of 20.0–30.0 °C. Furthermore, research works carried out in oceanic and desert climates exhibit comfortable temperatures of 20.2–20.9 °C and 22.0–25.0 °C respectively [29]. As such, the temperatures of 17, 20, and 22 °C were chosen in this study, since it is dealing with indoor thermal comfort in Malaysia, which is a tropical nation where air conditioning is commonly employed to control indoor temperatures. These temperatures are representative of various cooling setpoints that are conventionally employed in residential and commercial buildings. This research used 25.6 °C as starting room average indoor comfort temperature based in university buildings in Malaysia at according to a research of 130 participants [30].

3. Methodology

The room temperature control system is implemented with a closed-loop feedback mechanism to control a stable and desired temperature. The approach comprises specifying the components of the system, choosing an effective control method, and characterizing system performance. First, the structure of the control system is defined by a setpoint input, controller, plant depicting the air conditioner system, and a feedback loop. The error signal, as the difference between setpoint and actual room temperature, is fed to the controller. The hybrid control strategy comprises the integration of a PID controller along with a gain-scheduling function, whereby the PID controller regulates the temperature deviations and the gain-scheduling function regulates the control gains dynamically for efficient working. Fig 1 illustrated the typical closed loop feedback system using PID while Fig. 3 shows the HGSPID closed loop system.

The proposed air conditioning system is an automated self-regulating system that uses the fan speed control, the heater and the keypad to automatically monitor the room temperature and compare it with the predefined reference temperatures. The design has been developed using Simulink MATLAB software. This research used hybrid of gain scheduling and PID as controller to optimize room temperature. Fig. 3 and Fig. 4 below shows the block diagram of this research that consists of setpoint or desired temperature, controller block and plant transfer function. Fig. 3 demonstrated the conventional design while Fig. 4 represented the HGSPID closed loop feedback system using MATLAB.

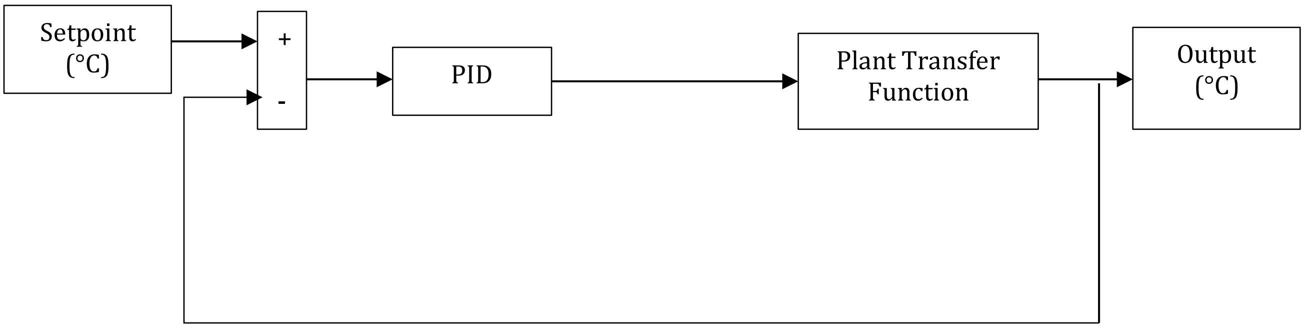

Fig. 1 *The block diagram of PID air conditioning control system*

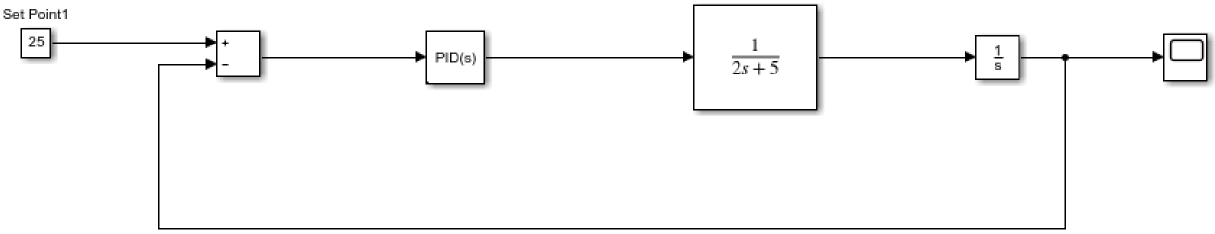

Fig. 2 *The block diagram of PID air conditioning control system using MATLAB*

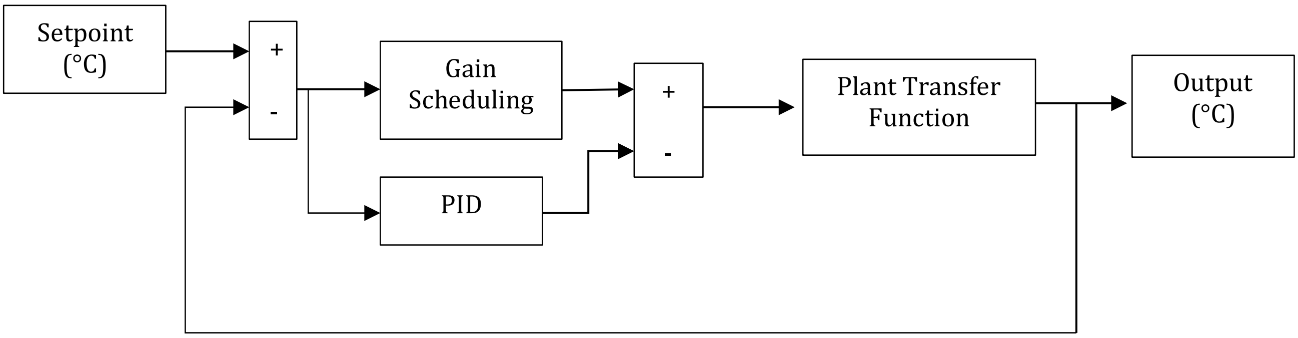

Fig. 3 *The block diagram of HGSPID air conditioning control system*

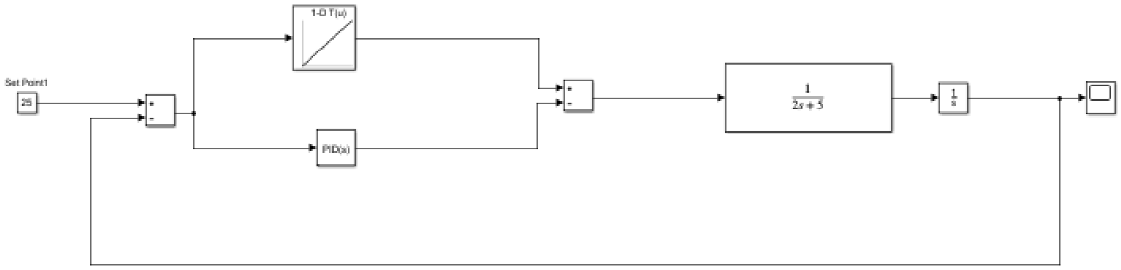

Fig. 4 *The block diagram of air conditioning control system using MATLAB*

3.1 PID Controller

For several processes, PID controllers can ensure acceptable performances with a simple method [31]. This controller is distinct in its capabilities as well because of the variety of components that operate within it [32]. The PID controller has three gain settings that can be adjusted or modified to improve performance. There are several adjustment method such as Manual Tuning (MT) or trial and error [33], Ziegler Nichols (ZN) and Cohen Coon (CC). Eq. 1 below expresses the PID controller's S-domain transfer function [34].

$$C(s) = K_P\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{1}$$

3.1.1 Manual Tuning

The optimal PID parameters for a system can be obtained using a MT or trial-and-error approach, where the user manually inputs several PID values until the optimal PID constants are reached. Nevertheless, this situation is difficult and ineffective since it requires a significant amount of time and manual effort to obtain the most efficient system response [35]. The controller parameters settings are based on observation of the response to reference or disturbance changes with the assistance of an expert, or the design is driven by empirical rules. The control-loop synthesis is time-consuming and its success is not guaranteed.

3.1.2 Ziegler Nichols

The dynamic characteristic of the process is denoted by the ultimate gain of a proportional controller and the ultimate period of oscillation of the loop in the Ziegler Nichols (ZN) method. Through the subsequent procedure, it typically ascertains the ultimate gain and duration of the actual process [36]. Fig. 5 demonstrated the *S*-shaped response curve for Ziegler Nichols.

- The feedback controllers' integral and derivative modes are switched off to generate a proportional controller.
- The automatic controller increases the proportional gain until the loop oscillates with constant amplitude.
- The duration of the oscillation is measured and documented as T, representing the final period, by utilising a time recording of the controlled variable.

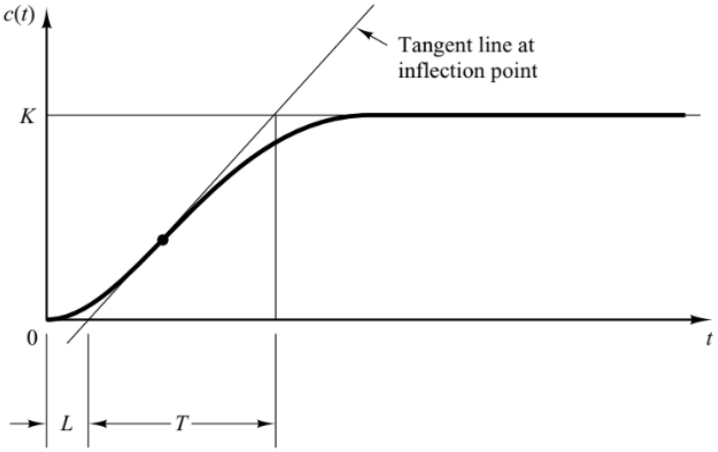

Fig. 5 *S-shaped response curve* [37]

3.1.3 Cohen Coon

The Cohen Coon (CC) method is also among the most robustly used strategies for tuning PID controllers. The CC tuning approach is an advanced version of the ZN method that incorporates additional system information to significantly enhance control performance. It is also referred to as a process reaction curve. Compared to the ZN tuning rules, the CC tuning rules are more applicable to a wider range of processes. When the dead time is less than twice the length of the time constant, the CC tuning rules perform well and can even be extended further if the process requires it [38]. Furthermore, one major issue with CC parameters is that they are not very robust. There is a chance that a small adjustment to the process parameters will make the closed-loop system unstable and result in oscillatory closed loop behavior like ZN [39]. This approach defines three parameters: steady state gain (α), time delay (L), and time constant (T) and (**τ**) is a relative dead time [40]. Cohen coon formula as describe below

$$\propto = \frac{K_p L}{T}$$

$$\tau = \frac{L}{(L+T)}$$

3.2 Gain Scheduling

The gain scheduling approach is commonly employed due to its crucial role in identifying quantifiable variables, known as scheduling factors, that accurately correspond to variations in process dynamics at different operating points. Gain scheduling involves an adjustment component that determines the system's operating point using scheduling variables and calculates the associated controller parameter values from a look-up table [41].

The gain scheduling control strategy creates a global controller that is non-linear by utilizing local controllers that have been optimized for distinct operating points. The controller is specifically built to accommodate different tuning values for the number of operating points needed for non-linear operation. It is recognized as a collection of controllers. The key of this technology is that the controller parameters are dynamically changed in real-time as the operating conditions evolve during operation [42] [43]. The look up table design for this research is illustrated in Fig. 6 below.

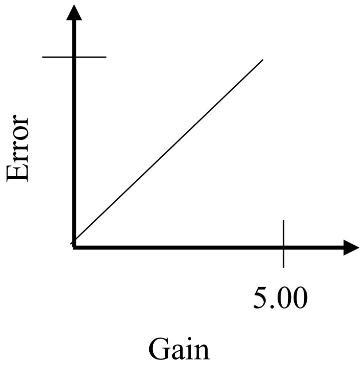

Fig. 6 *Look up table for gain scheduling*

4. Results and Discussion

This section discusses the proposed HGSPID efficiency in terms of transient response and settling time. The performance of HGSPID was compared with conventional PID controller using MT, ZN and CC tuning method to calculate the improvement. This research test for several temperature which is 17°C, 20°C, and 22°C at multiple loop condition to test the robustness of the system.

Fig. 7 below shows the results for ideal room temperature is set to 17°C. The MT produce undershoot at 15.82°C, ZN 14.77°C and HGSPID 16.86°C. During increasing the temperature at 25.6°C MT produce 26.73°C overshoot, ZN 27.83°C HGSPID 25.74°C. For both condition, CC does not produce undershoot or overshoot.

For settling time, ZN and HGSPID give shortest time at 4.84 seconds, MT at 8.59 seconds and CC at 10.39 seconds. Table 1 below present the performance percentage error for four difference tuning method. Based on the results, HGSPID yield the best output with small overshoot and shortest settling time.

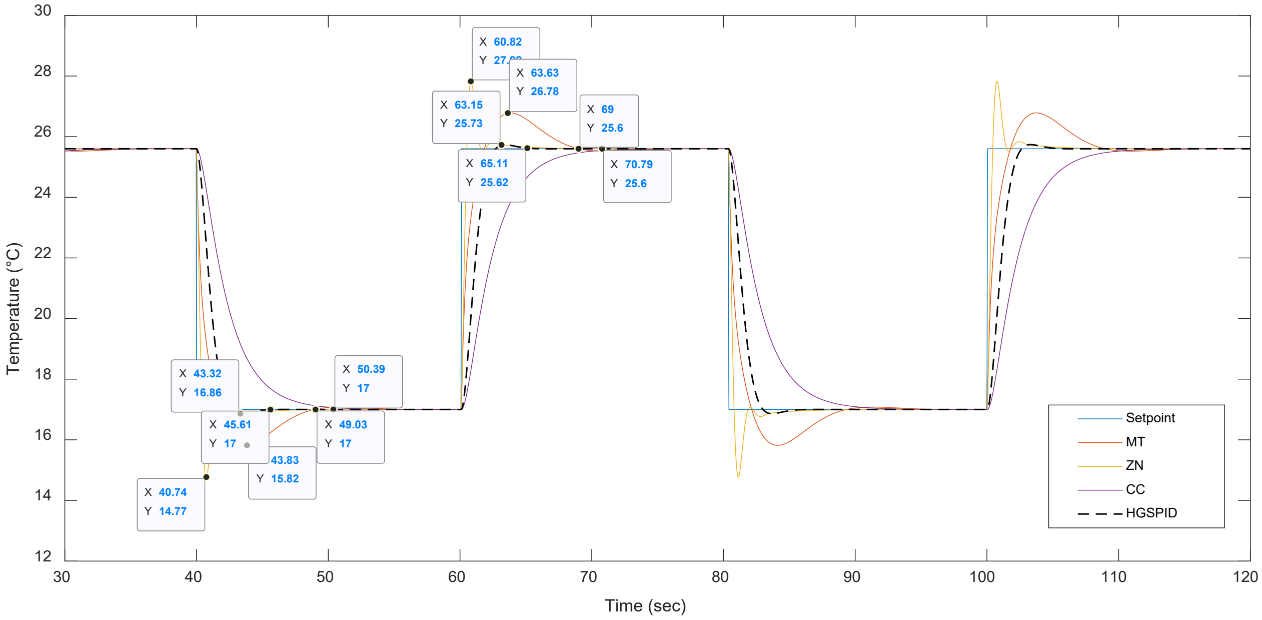

Fig. 7 *Temperature performance at 17°C*

Table 1 *Percentage error 17°C*

Method	Overshoot (%)	Settling time (%)
MT	6.94	21.48
ZN	13.11	12.1
CC	0	25.98
HGSPID	0.82	12.1

The findings at a desired temperature transient response of 20°C are depicted in Fig. 8 below. The MT exhibits an undershoot at a temperature of 19.25°C, whereas the ZN shows an undershoot at 18.55°C and the HGSPID at 19.91°C. When the temperature was raised by 25.6°C, MT resulted in an overshoot of 26.73°C, ZN produced an overshoot of 27.05°C, and HGSPID had an overshoot of 25.68°C. CC does not exhibit either undershoot or overshoot for both conditions. The settling time is shortest at 5.77 seconds for the ZN and HGSPID methods, 12.26 seconds for the CC method and 13.28 seconds for the MT method. The table 2 below displays the percentage inaccuracy at 20°C for four different tuning methods. According to the findings, HGSPID produced the most ideal outcomes, with little overshoot and the shortest period of time taken to settle.

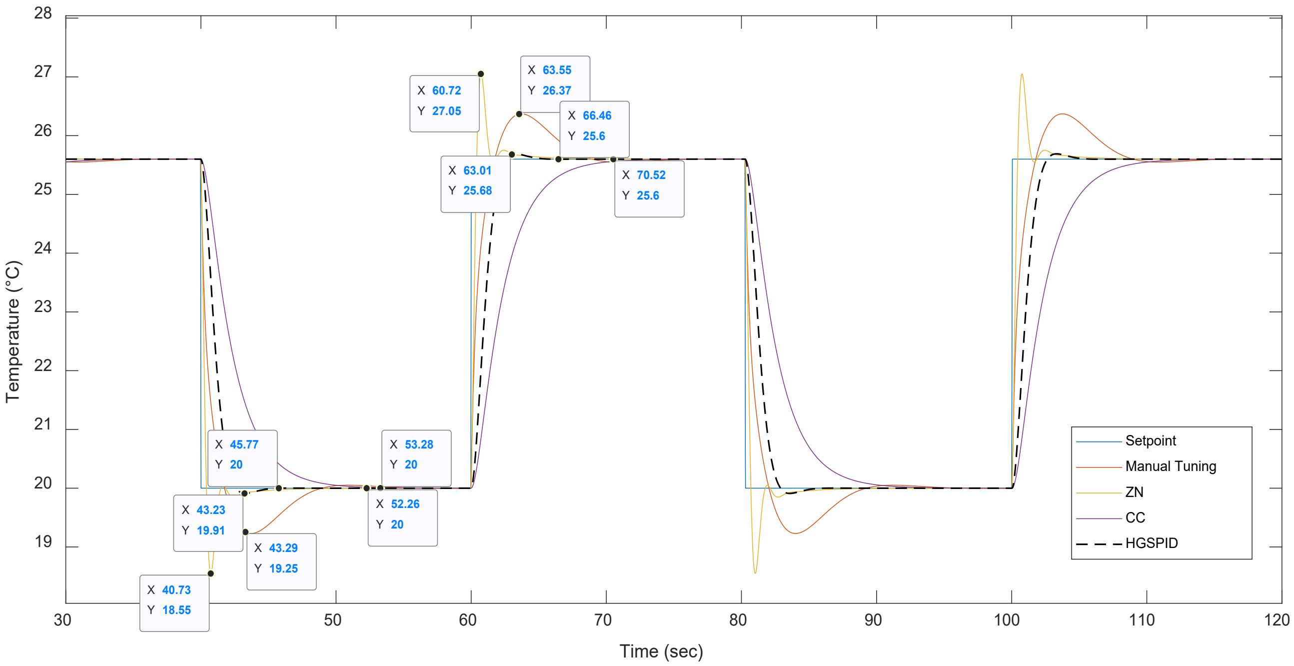

Fig. 8 *Temperature performance at 20°C*

Table 2 *Percentage error 20°C*

Method	Overshoot (%)	Settling time (%)
MT	3.75	33.20
ZN	7.25	14.43
CC	0	30.65
HGSPID	0.45	14.43

Fig. 9 below shows the results at the required temperature of 22°C. The MT transient response displays an undershoot at 21.51°C, whereas the ZN and HGSPID display undershoots at 21.09°C and 21.95°C, respectively. MT caused an overrun of 26.08°C, ZN produced an overshoot of 26.53°C, and HGSPID produced an overshoot of 25.66°C when the temperature was raised by 25.6°C. For both scenarios, CC did not show any signs of undershoot or overshoot. For the ZN and HGSPID techniques, the settling time is the shortest at 3 seconds; for the CC method, it is 12.01 seconds; and for the MT method, it is 12 seconds. The performance percentage error for the four difference tuning methods at 22°C is shown in Table 3 below. The results show that HGSPID produces the best results with the least amount of overshoot and shortest settling time.

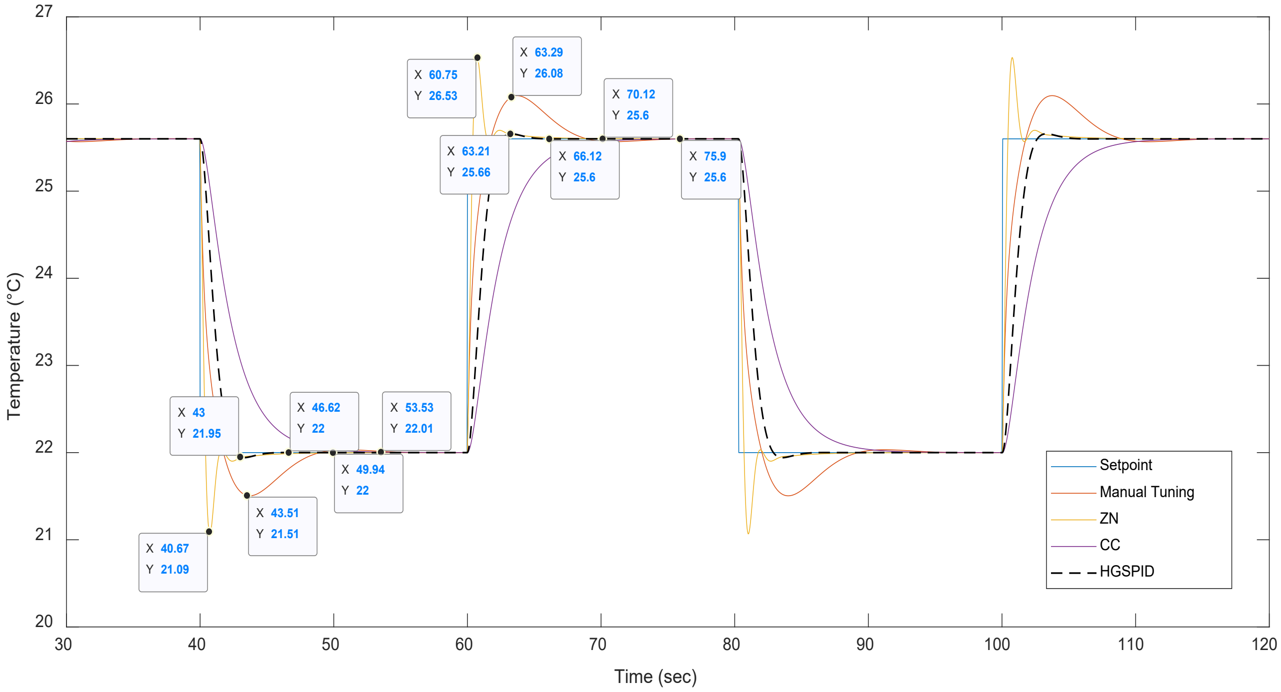

Fig. 9 *Temperature performance at 22°C*

Table 3 *Percentage error 22°C*

Method	Overshoot (%)	Settling time (%)
MT	2.22	30.00
ZN	4.34	7.5
CC	0	30.02
HGSPID	0.23	7.5

Based on the results for three different reference temperatures, the HGSP controller can be observed to improve the conventional PID using MT, ZN and CC performance in term of transient response and settling time. Even though it produces overshoot, the condition is still acceptable as it less than 5%.

5. Conclusion

This paper presents an HGSPID controller designed for the purpose of regulating the temperature. The HGSPID system combines gain scheduling with PID controller. The findings show that the HGSPID is able to control the temperature better in term of settling time in comparison to the conventional PID controller. The HGSPID controller is observed to produce overshot at a small acceptable value. This demonstrates that the suggested controller is capable of efficiently regulating the temperature to reach the desired set point quickly and maintain it at the desired level and overcome the conventional PID controller. This system is robust and may be utilized in various settings such as homes, schools, offices, laboratories, and other sectors. In future studies, this research will be expanded to incorporate the optimization of the parameters by utilizing metaheuristic methods such as particle swarm optimization, gravitational search algorithm, and other techniques to enhance the system.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Anith Khairunnisa Ghazali, Nor Azlina Ab. Aziz, Thangavel Bhuvaneswari Author Y;* ***data collection:*** *Anith Khairunnisa Ghazali; Nor Azlina Ab. Aziz* ***analysis and interpretation of results:*** *Anith Khairunnisa Ghazali,* ***draft manuscript preparation:*** *Anith Khairunnisa Ghazali, Nor Azlina Ab. Aziz, Thangavel Bhuvaneswari, Venugopal Chitra. All authors reviewed the results and approved the final version of the manuscript.*

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