ADAPTIVE PID CONTROLLER BASED ON FUNCTION TUNER FOR HVAC SYSTEMS

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Abstract - This paper introduces a function tuner-based adaptive PID controller for HVAC systems. An experimental setup has been established for the HVAC system and the performance of the function tuner-based adaptation mechanism has been assessed on the HVAC experimental setup. The acquired results indicate that the function tuner mechanism is of highly effective adaptation capabilities and control performance.

Keywords - Adaptive Control, Model-Free Control, Function Tuner Mechanism, HVAC System, PID Controller

I. INTRODUCTION

Heating, ventilation, and air-conditioning (HVAC) systems require control of environmental temperature, humidity and CO2 so as to enhance life quality[1][2]. PID controller structure is one of the most effective and widely used control strategies for HVAC systems owing to its simple design, ease of implementation and robustness.

In technical literature, there are various studies related to PID control of HVAC systems. Astrom et al. proposed an automatic tuning method for digital controllers based on relay feedback, specifically designed for HVAC systems[3]. The results in [3] demonstrate that the proposed algorithm effectively determines appropriate controller parameters and provides stable and efficient control performance in HVAC systems. Wemhoff introduced a PID coefficient calibration method for HVAC systems aimed at reducing energy consumption without compromising indoor comfort[4].

The findings in [4] indicate that optimized adjustment of proportional and integral gains can achieve up to 35% energy savings and enhance temperature control accuracy by over 50%, indicating the effectiveness of this approach for improving HVAC system efficiency. Bi et al. have been developed an approach employing relay and/or step-response identification techniques to automatically adjust PID parameters for HVAC systems[1]. Wang et al. introduced a human-imitating intelligent PID control strategy designed for the nonlinear, time-delay, and strongly coupled characteristics of HVAC systems[5]. Liu et al. proposed a PSO-based PID control method for HVAC systems.

This optimization-based design method, developed to solve the parameter tuning problems of classical PID controllers, offers highly effective control performance[6]. Wang et al. proposed a simple and efficient PID autotuning method for application in HVAC systems[2]. The control methodology is based on estimating system dynamics using low-order plus dead-time models and adaptively adjusting the PID parameters accordingly[2]. İmal utilized various adaptation algorithms of Z-N variant in the adaptation of PID controller parameters for the control of HVAC systems[7]. Geng and Geary introduce a study on the influence of disturbances and process time delays on the PID control performance of HVAC systems[8]. Wang et al presents a neuron-based adaptive PID controller designed to handle modeling uncertainties and nonlinearities in single-zone HVAC systems[9]. The introduced structure demonstrates the controller's self-learning and self-adaptive capabilities, along with its superior resistance to white noise interference compared to conventional PID control[9].

The adaptation mechanism originally introduced by Woo et al. [10] for fuzzy PID controller structures has been extended in this study to enable parameter adaptation in conventional PID controllers. The effectiveness of the proposed adaptation mechanism has been assessed through its application to HVAC systems. The obtained results demonstrate that the proposed approach achieves highly efficient and robust control performance.

The remainder of this paper is organized as follows: Section 2 describes the proposed adaptation mechanism within the conventional PID controller framework. Section 3 presents the details of the HVAC system along with the experimental studies conducted. Finally, Section 4 provides concluding remarks and summarizes the main findings of the study.

II. ADAPTIVE PID CONTROLLER BASED ON FUNCTION TUNER MECHANISM

The function tuner mechanism introduced by Woo et al is designed to adjust the fuzzy PID controller gains by increasing the integral term and decreasing the derivative term according to the magnitude of the error[10]. Inspired by this mechanism proposed by Woo et al. [10] and building on this concept, the following adaptation rules are proposed for the adaptive PID controller:

$$K_p = K_{p0}$$
$$K_i = K_{i0} f\left(e(t)\right) \quad (1)$$
$$K_d = K_{d0} g\left(e(t)\right)$$

where

$$f\left(e(t)\right) = a_1 \left|e(t)\right| + a_2$$
$$g\left(e(t)\right) = b_1 \left(1 - \left|e(t)\right|\right) + b_2 \quad (2)$$

As evident from the corresponding functions, an increase in the error term enhances the dominance of the integral component of the PID controller while diminishing the influence of the derivative component. In this manner, the integrator is emphasized to minimize the steady-state error associated with larger error values, whereas the contribution of the derivative term is reduced to suppress oscillatory behavior.

During the course of our study, it has been observed that the relative error term($r_e(t)$) provided better performance compared to the direct error term($e(t)$); therefore, the learning rules have been refined accordingly as follows:

$$K_p = K_{p0}$$
$$K_i = K_{i0} f\left(r_e(t)\right) \quad (3)$$
$$K_d = K_{d0} g\left(r_e(t)\right)$$

where $r_e(t) = \dfrac{e(t)}{r(t)}$, $r(t) \neq 0$ and

$$f\left(r_e(t)\right) = a_1 \left|r_e(t)\right| + a_2$$
$$g\left(r_e(t)\right) = b_1 \left(1 - \left|r_e(t)\right|\right) + b_2 \quad (4)$$

III. SIMULATION RESULTS

The control performance of the adaptive PID controller based on function tuner(APIDFT) has been assessed on HVAC system. In this study, an experimental setup has been assembled to control key environmental parameters—temperature, relative humidity, and carbon dioxide (CO_2)—within a closed environment. The experimental apparatus consists of a sealed and lockable test chamber.

A. HVAC System

The experimental setup is given in Figure 1. To reduce thermal interference from the external environment and improve energy efficiency, the chamber floor has been covered with a thermal insulation layer. Real-time monitoring of the internal environmental conditions has been achieved using a high-precision sensing unit. In this setup, the Sensirion SCD40 sensor module was chosen due to its ability to simultaneously measure temperature (T), relative humidity (RH), and carbon dioxide (CO_2) concentration within a single integrated platform. The sensor data are continuously transmitted to the control system to provide immediate feedback.

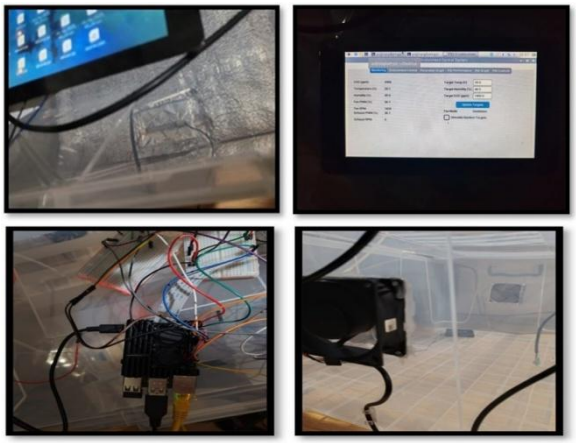


Figure 1. HVAC System Demo(Experimental Setup)

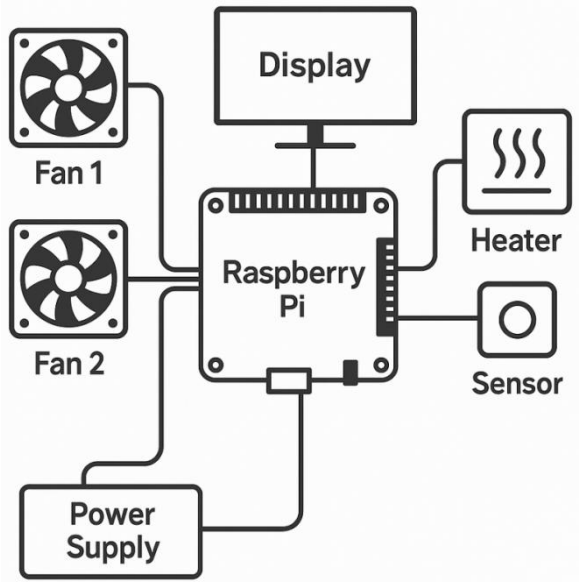


Figure 2. Raspberry Pi–Based Demo System

As shown in Figure 2, a Raspberry Pi single-board computer functions as the system's main control unit. The data collected from the Sensirion SCD40 sensor are processed by the Raspberry Pi, where control algorithm—implemented in the Python programming language—are executed. The controller continuously compares the real-time sensor readings with predefined target setpoints to determine which actuator (heater, cooling fan, or ventilation fan) should be activated to maintain desired environmental conditions.

B. Real Time Control of HVAC System via Adaptive PID Controller based on Function Tuner

The tracking performance of the APIDFT is illustrated in Figure 3 for temperature. The evaluation of controller parameters(Ki,Kd) are depictured in figure 4, where Kp, Ki,Kd,a1,a2,b1,b2 have been set to

25,0.2,0.9,0.6,0.4,0.8 and 0.2, respectively. A detailed examination of these results reveals the presence of short-duration transient peaks in the Ki parameter, which predominantly occur during transitions between reference setpoints.

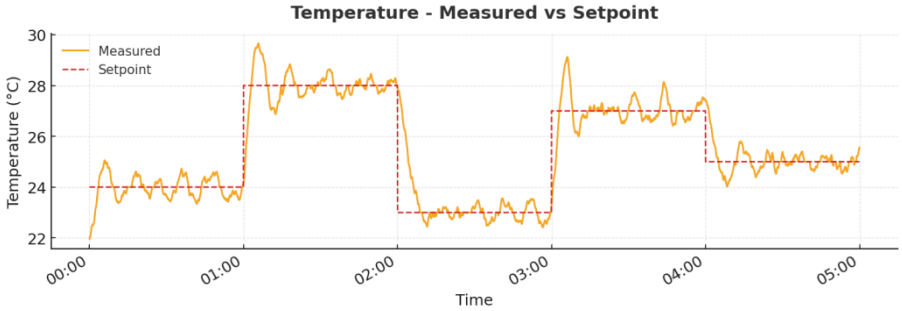


Figure 3. Tracking performance of Adaptive PID controller based on Function Tuner(Temperature).

For instance, at approximately 02:00, the Ki value exhibits a pronounced increase, facilitating the reduction of steady-state error and enhancing the convergence of the system response to reference. Likewise, the dynamic variation of the Kd parameter, reflecting its sensitivity to the instantaneous tracking error, is illustrated in figure 4. The characteristic responses illustrated in figures 3 and 4 demonstrate that the controller effectively drives the system temperature toward the desired reference value, ensuring accurate tracking and stable convergence within the closed-loop operation.

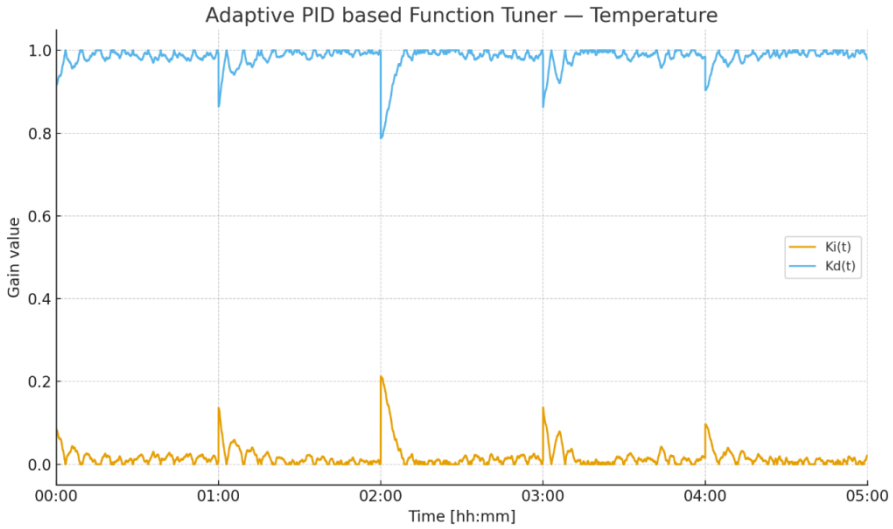


Figure 4. Evaluation of PID parameters(Temperature).

Similarly, the control performance of the APIDFT controller architecture in regulating humidity is illustrated in Figure 5 and 6, demonstrating the system's ability to maintain the desired humidity levels with satisfactory tracking accuracy. The parameter values of PID and function tuner mechanism have been initialized as Kp=30, Ki=0.05, Kd=1, a1=0.6, a2=0.4, b1=0.8, b2=0.2.

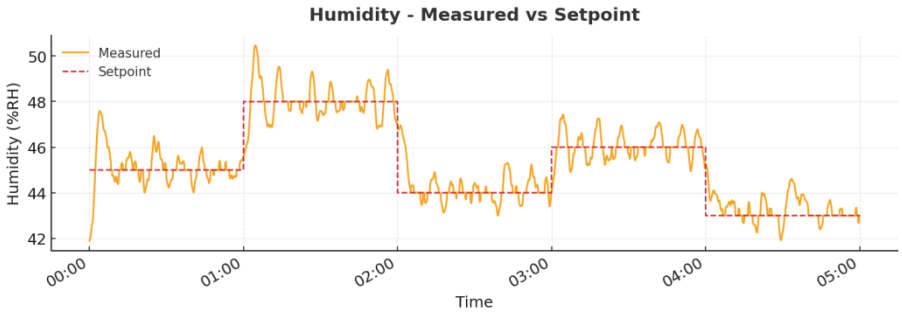


Figure 5. Tracking performance of Adaptive PID controller based on Function Tuner(Humidity).

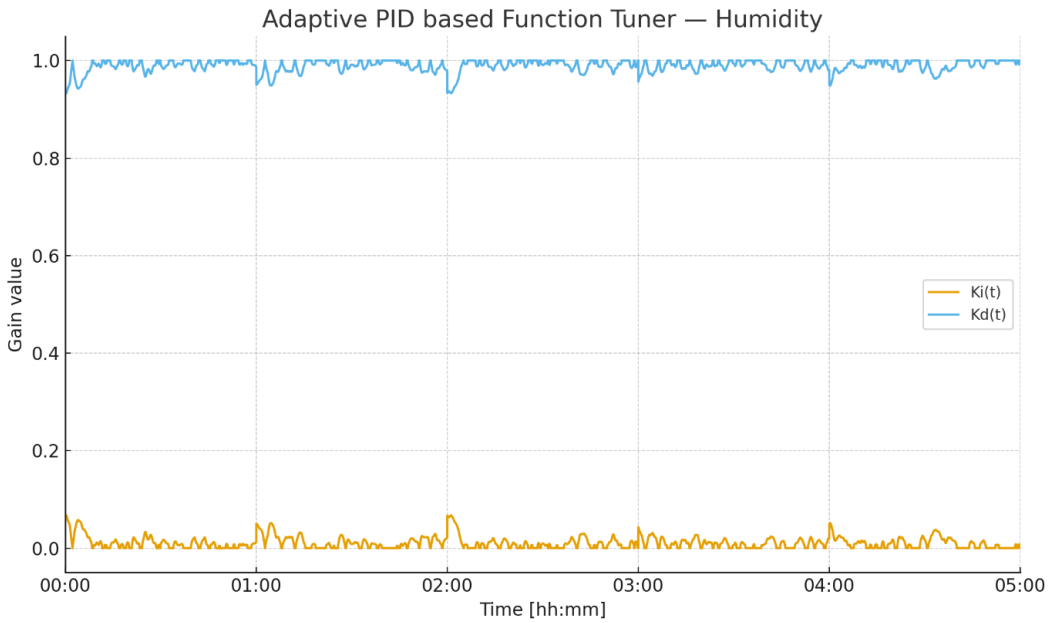


Figure 6. Evaluation of PID parameters(Humidity).

The humidity level of the outdoor environment exceeds the desired staircase reference signal. It is noteworthy that the actuator in the humidity control channel does not directly produce or remove moisture; instead, it influences the humidity indirectly through air exchange (inlet–exhaust) and thermal interactions within the heating subsystem. This inherent physical limitation is distinctly reflected in the temporal evolution of the controller gains. During transient intervals, the Ki parameter exhibits short-term increases in response to humidity deviations arising from valve dynamics, airflow variations, or heating effects.

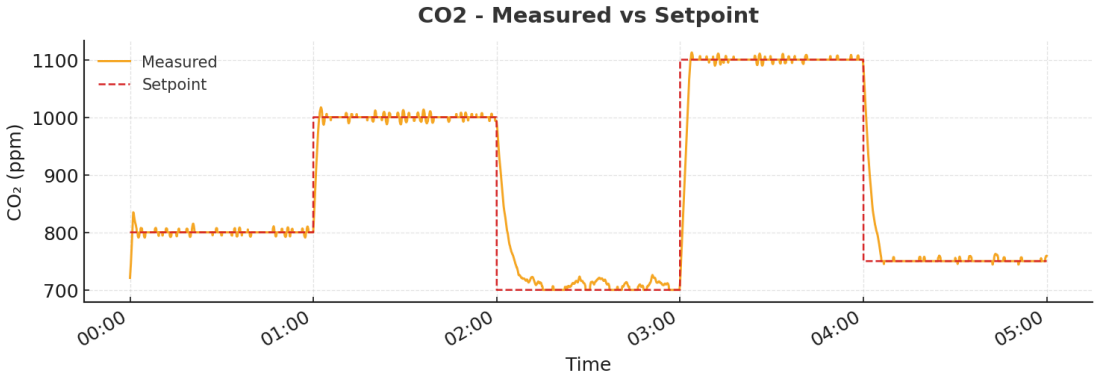


Figure 7. Tracking performance of Adaptive PID controller based on Function Tuner(CO_2).

Under standard indoor conditions, the ambient CO_2 concentration typically remains around 950 ppm. However, in the experimental setup of this study, the CO_2 level within the enclosed test chamber has been intentionally stabilized at approximately 1200 ppm. This adjustment has been necessary because the fan-based control mechanism regulates the CO_2 concentration primarily through air exchange with the external environment. Once the proposed adaptive control system is activated, the fan operation successfully reduces and maintains the CO_2 concentration below 1200 ppm, demonstrating effective closed-loop regulation and rapid dynamic response. Conversely, when the control mechanism is deactivated, the CO_2 concentration gradually increases and is stabilized near 1200 ppm again, reflecting the natural equilibrium state of the confined space in the absence of active ventilation.

The control performance of the APIDFT controller for carbon dioxide(CO_2) regulation, along with the corresponding variations in the controller parameters Ki and Kd , is presented in Figures 7 and 8 where Kp, Ki,Kd,a1,a2,b1,b2 parameters have been initialized to 1,0.01,1,0.6,0.4,0.8 and 0.2, respectively. These figures illustrate the adaptive behavior of the controller in response to dynamic changes in CO_2 concentration, revealing its ability to adjust parameter values in real time to achieve precise and stable tracking of the desired reference levels.

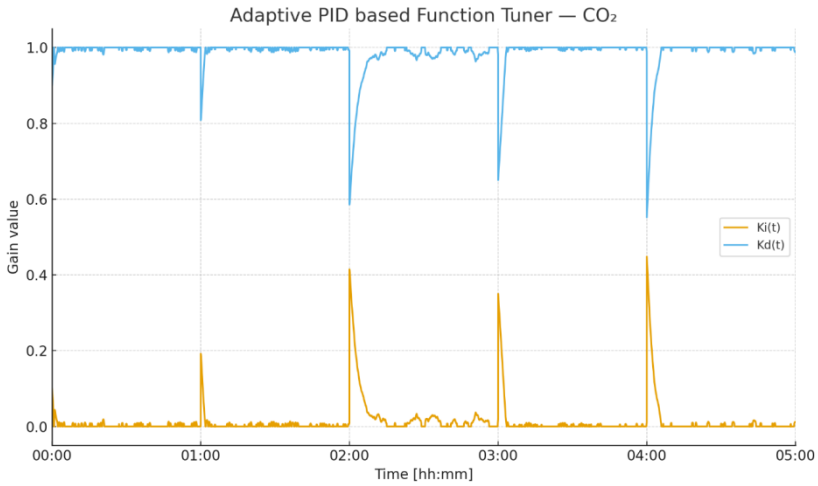


Figure 8. Evaluation of PID parameters(CO_2).

During transitions between reference points, distinct transient peaks in the Ki and Kd parameters have been observed for both increasing and decreasing reference values. These peaks indicate the controller's adaptive response aimed at promptly reducing steady-state error. Specifically, the integral term becomes more dominant during the transition phase to suppress transient deviations rapidly, whereas the derivative term gains significance as the system output converges toward the reference signal, enhancing stability in tracking performance.

In conclusion, the adaptive control architecture implemented in the CO_2 dynamically adjusts its parameters—making dominant the integral action during transient states and the derivative action during steady-states. This adaptive transition enables rapid convergence toward the reference value while maintaining stable steady-state performance.

IV. CONCLUSION

In this paper, the function tuner mechanism proposed by Woo et al. for fuzzy PID controller structures has been adapted to classical PID controller structures. Relative tracking error information has been deployed instead of the tracking error in the function tuner adaptation mechanism. The performance of the adaptation mechanism has been experimentally examined on an HVAC system. The findings indicate that the function tuner mechanism, originally proposed by Woo et al., also provides highly effective performance for classical adaptive PID controller structures.

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