ADAPTIVE SELF-TUNING DECOUPLED CONTROL OF TEMPERATURE AND RELATIVE HUMIDITY FOR A HVAC SYSTEM

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ABSTRACT

This paper presents an adaptive self-tuning decoupled controller for control of temperature and relative humidity of a heating, ventilating, and air conditioning (HVAC) system in order to achieve comfort conditions for occupants. It is important to be able to control temperature and relative humidity independently. Because of interaction of these variables in some industrial processes, it is necessary to use decoupling techniques to achieve accurate control. In this regards, we have used recursive least square (RLS) algorithm for identification of the HVAC system to self-tuning of proportional-integral-derivative (PID) controller for temperature and relative humidity. Simulation results demonstrate that the adaptive self-tuning decoupled controller is applicable for this HVAC system.

Keywords: Adaptive control, RLS algorithm, HVAC system, PID controller, self-tuning decoupled control.

1. INTRODUCTION

Heating, ventilating, and air-conditioning (HVAC) systems require control of environmental variables such as temperature, relative humidity, pressure etc. the most of the controllers that have used in HVAC systems are of Proportional-Integral-Derivative (PID) type. HVAC systems used in living and industrial buildings should fulfill thermal comfort needs and indoor air quality. The comfort of the people in their living indoor environment is partially dependent on some factors, as quality, humidity, pressure, and temperature of air inside the building. The purpose of the HVAC system of a building is to provide complete thermal comfort for its occupants. Hence, it is necessary to understand the thermal and humidity aspects of the human body in order to design an effective HVAC system. HVAC system is a non-linear and time variant system. It is difficult to achieve desired tracking control performance. Over the past few years, several methods for determining of parameters of applied controllers on these systems have been developed. As indicated in [1], more than 95% of the control loops are of PID type in process control. Over the years, there are many formulas derived to tune the PID controllers for stable processes, such as Ziegler-Nichols, Cohen-Coon, internal model control, integral absolute error optimum (ISE, IAE, and ITAE), and recently proposed tuning methods[2,3].

Some researchers have been focused on decoupled control of temperature and relative humidity of HVAC systems. For instance, [4-6]. Some studies as [7,8] are about application of PID controller in the HVAC systems. We know HVAC systems are non-linear and time
variant, so, direct controls of these systems are difficult. Identification approaches are very useful methods for achieve approximate models. In this regards, some of researchers use different identification methods for apply on this systems as [9]. RLS identification is one of these methods.

In this paper we developed and simulated an adaptive self-tuning algorithm for tuning PID parameters for a decoupled HVAC system in order to control of temperature and relative humidity of a thermal zone, where thermal comfort of the system is evaluated.

This paper organized as follow: In the first part of this paper the HVAC system and thermal space model is described. The second part described the non-interacting control in a HVAC system. After describe of PID controller in a separate section adaptive self-tuning algorithm are presented. In the last part simulation result are presented.

2. THE HVAC SYSTEM AND THERMAL SPACE MODEL

We consider the single-zone HVAC system shown in Figure 1. Components of this system include thermal space, heating/cooling coil, humidifier/dehumidifier, mixing box, air filter, supply and return fans, filters, dampers, and ductwork. In this system, initially, fresh air enters and mixes with 75% of the return air, and remaining air is exhausted. Then, mixed air passes through the heat exchanger components and finally by supply fan enter to thermal zone. Supply air satisfies the thermal space. By changing of thermal load, the system controller simultaneously varies volumetric flow rate of air and water, so that the desired set-points in temperature and relative humidity are maintained.

The differential equations describing the dynamic behavior of the HVAC system in Figure 1, can be conclude from energy-mass equations as follow.

\[
\frac{dW_z}{dt} = \frac{W_z - W_{z_a} + M_z}{V_z} \rho V_z \tag{1}
\]

\[
\frac{dT_z}{dt} = \frac{(T_z - T_{w_a})}{V_z} + \frac{0.25(T_z - T_{w_a})}{V_{he}} f_a + \frac{f_a (0.25W_{w_a} + 0.75W_z - W_z)}{C_{pa} V_{he}} \frac{\rho h_{fa} f_a}{\rho C_{pa} V_{he}} \tag{2}
\]

\[
\frac{dT_z}{dt} = \frac{(T_z - T_{w_a})}{V_z} + \frac{h_{fg} (W_z - W_{z_a})}{C_{pa} V_z} + \frac{(Q_z - h_{fg} M_z)}{\rho V_{pa} C_{pa}} \tag{3}
\]
3. NON-INTERACTIVE CONTROL

In order to control of multi-input multi-output (MIMO) systems, we can use many different methods. One of these methods is non-interactive control method. In this method the feedback is used transform the MIMO system, from the input-output point of view, to an aggregate of independent single input SISO channels.

Assume a system in state-space form with m input $u_i$ and n output $y_j$ that $i=1,2,...,m$ and $j=1,2,...,n$. for this system we can write

$$\dot{x}_i = f_i(x) + \sum_{j=1}^{m} g_{ij}(x)u_j$$

$$y_i = h_i(x) \quad 1 \leq i \leq n$$

The problem is to find a feedback control law as follow

$$u_i = \psi_i(x) + \sum_{j=1}^{m} \delta_{ij}v_j$$

Such that for the closed-loop system

$$\dot{x}_i = f_i(x) + \sum_{j=1}^{m} g_{ij}(x)\psi_i(x) + \sum_{j=1}^{m} \sum_{j=1}^{m} (g_{ij}(x)\delta_{ij}v_j)$$

$$y_i = h_i(x)$$

The resulting closed-loop system is a decoupled system in which the $i^{th}$ output is controlled only by $i^{th}$ input. The non-interacting control law is given by

$$u = -A^{-1}(x)b(x) + A^{-1}(x)v$$
Where $A(x)$ is decoupling matrix, for definition and calculation see [4], $v$ is the new input for control of control variables independently, and $b(x)$ is defined as

$$
b(x) = \frac{\partial}{\partial x} \left[ \sum_{i=1}^{m} \frac{\partial h_i}{\partial x_j} f_i(x) \right] f(x)\frac{\partial}{\partial x} \left[ \sum_{i=1}^{m} \frac{\partial h_i}{\partial x_j} f_i(x) \right] f(x) M \left[ \sum_{i=1}^{m} \frac{\partial h_i}{\partial x_j} f_i(x) \right] f(x)
$$

(8)

For presented HVAC system we want to control temperature and relative humidity of the zone. In this regards, we need two control loops and two control signals. After calculation of $A(x)$ and $b(x)$ we can obtain the non-interacting control signals as following expression

$$
\begin{bmatrix}
  u_1 \\
  u_2 
\end{bmatrix} = \begin{bmatrix}
  (\alpha_1 \beta g_{11}(x) + 1.388 \alpha_1 \beta_4 g_{13}(x)) \\
  -\alpha_2 x_4 g_{11}(x) - 1.388 \alpha_2 x_4 \beta_4 \\
  -g_{13}(x) \\
  g_{11}(x)
\end{bmatrix} \begin{bmatrix}
  v \\
  B_1(x) \\
  v_2 - B_2(x)
\end{bmatrix}
$$

(9)

Where $x_1 = W_a$, $x_2 = T_a$, $x_3 = T_h$, $x_4 = f_a$. And

$$
g_{11} = (5000 \alpha_1 W_a + 107 \alpha_1 - \alpha_1 W_a - 1.388 \alpha_1 x_2 + 1.388 \alpha_1 W_a - 2.776 \times 10^{-4} \alpha_2 x_3 + 3.85 \times 10^{-4} \alpha_2 x_3 + 29.7 \times 10^{-3} \alpha_a)
$$

(10)

$$
g_{12} = (5 \times 10^{-4} \beta_4 x_1 - \beta_2 x_2 + (\beta_1 - \beta_2 - 2.1 \times 10^{-4} \beta_3) x_3 + 0.25 \beta_5 W_a + \beta_5 W_a + 0.016 \beta_4)
$$

(11)

$$
g_{13}(x) = \alpha_1 (W_a - 0.0214)) + 2 \times 10^{-4} \alpha_2 x_1 + \alpha_1 x_2 + (2.776 \times 10^{-4} \alpha_2 x_1)
$$

(12)

$$
\begin{align*}
\alpha_1 &= 60 / V_z \\
\alpha_2 &= 60 h_{fc} / C_{pa} V_z \\
\alpha_3 &= 1 / \rho_a C_{pa} V_z \\
\alpha_4 &= 1 / \rho_a V_z \\
\beta_1 &= 60 / V_{he} \\
\beta_2 &= 15 / V_{he} \\
\beta_3 &= 60 h_w / C_{pa} V_{he} \\
\beta_4 &= 6000 / \rho_a C_{pa} V_{he}
\end{align*}
$$

(13)

$$
B_1(x) = (-\alpha_2 x_4 - 2.776 \times 10^{-4} \alpha_2 x_4) (f_a(x) + g_1(x)x_4) + (-1.388 \alpha_2 x_4) g_{12}(x) x_4 + (-3.85 \times 10^{-4} \alpha_2 x_4) \\
\times (f_4(x) + g_{13}(x)x_4) + (-x_4 g_{11}(x))
$$

(14)

$$
B_2(x) = (2 \times 10^{-4} \alpha_2 x_4) (f_1(x) + g_{11}(x)x_4) + (\alpha_1 x_4) (g_{12}(x)x_4) + (2.776 \times 10^{-4} \alpha_2 - \alpha_1) (f_4(x) + g_{13}(x)x_4) x_4 + (-g_{13}(x)x_4)
$$

(15)
In Eq. 14 and Eq. 15 \( f_1(x) \) and \( f_3(x) \) are

\[
\begin{align*}
    f_1(x) &= 5000\alpha_z M_z - 1.388\alpha_z (Q_z - h_{fg} M_z) \\
    f_3(x) &= \alpha_z (Q_z - h_{fg} M_z)
\end{align*}
\]

(16)

4. PID CONTROLLER

A PID controller is a kind of linear controller, as it composes the control error according to the setting value and process output and then makes the controller output value based on the linear resultant of error’s proportion, integral and derivative.

For a PID controller, the control signal at time \( t \) is determined from

\[
u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}
\]

(17)

Where \( u(t) \) is the controller output, \( K_p \) is the proportion parameter, \( K_i \) is the integral parameter, \( K_d \) is derivative parameter, \( e(t) \) is the error signal at time \( t \) defined as \( e(t) = y_{sp}(t) - y(t) \), where \( y_{sp} \) is the set point for process output at time \( t \) and \( y(t) \) is process output at time \( t \).

5. ADAPTIVE SELF-TUNING CONTROL ALGORITHM

This is a traditional adaptive filter algorithm that is useful for identification of control systems. It estimates the current parameter vector \( \hat{\theta}(k) \) based on the previous estimated vector \( \hat{\theta}(k-1) \), as follows [5,6]:

\[
\hat{\theta}(k) = f(\hat{\theta}(k-1), D(k), k)
\]

(18)

Where, \( D(k) \) denotes data available at time \( k \), and \( f(.,.,.) \) denotes an algebraic function, the form of which determines the specific algorithm. In the case of dynamic system, data \( D(k) \) normally consider the form of present and past observation of the system outputs and inputs. For multi-parameter system, this form can be represented as follows:

\[
y(k) = \psi^T(k)\theta
\]

(19)

Where,

\[
\psi(k) = [-y(k-1),..., -y(k-m), u(k),..., u(k-m)]^T
\]

(20)

\[
\theta = [a_1, ..., a_m, b_1, ..., b_{m+1}]^T
\]

(21)

The estimation of the parameters vector \( \theta \) is performed in a way such that the estimated \( \hat{\theta}_r \) minimizes the cost index \( J(r) \) where \( r \) denotes the number of sets of measurement,

\[
J(r) = \sum_{k=1}^{r} (y(k) - \psi(k)^T \hat{\theta}(k))^2
\]

(22)

Equation (5) can be written in a recursive form as:
\[ \hat{\theta}(k) = \hat{\theta}(k-1) + P(k)\psi(k)(y(k) - \psi^T(k)\hat{\theta}(k-1)) \]  

(23)

\[ P(k) = [P(k-1) - \frac{P(k-1)u(k)\psi^T(k)P(k-1)}{1 + \psi^T(k)P(k-1)\psi(k)}] \]  

(24)

We use from this algorithm for identification of HVAC system introduced in previous section. Figure 2 shows the diagram sketch of RLS-PID control of decoupled HVAC system.

6. SIMULATION RESULTS

For instance, we consider a system by nonlinear equation as follow

\[ y(t) = \frac{y^2(t-1)}{1 + y^2(t-1)} + u(t) \]  

(25)

Where \( u(t) = 0.4\sin(2\pi t / 50) \) for \( t = 0, 1, 2, \ldots, 100 \) and \( u(t) = 0.3\sin(2\pi t / 50) + 0.1\sin(2\pi t / 5) \) for \( t = 101, 102, \ldots, 200 \).

Figure (3) shows the proposed identification result of the system that introduced in Eq. 25.

The normalized error of the identification is 0.2119 that is a performance measure defined as \( E_n(t) = (e \cdot e^T) / (y \cdot y^T) \), where T is a transpose of the vector.

After identification model is completed, the tracking operation takes command of the RLS process control to track the desired set-points \( r_T(t) = -25u(t) + 50u(t-200) \), that \( t = 0, 1, \ldots, 200 \) for Temperature and \( r_{R.H}(t) = -10u(t) + 20u(t-100) \), that \( t = 0, 1, \ldots, 200 \) for Relative Humidity. The results of tracking performance are illustrated in figure (4) and figure (5) with the mean square error (MSE) 0.1343 for the plant and for RLS self tuning algorithm response of 0.023.
Fig. 3. RLS algorithm identification of a nonlinear system

Fig. 4. Output results of tracking operation for Temperature
In this paper, the performance of a HVAC system that uses a nonlinear decoupling algorithm for control of temperature and relative humidity is studied. We show that decoupling control law works satisfactorily. We used RLS algorithm for identification of the system and results of the identification are used for tuning of PID controller parameters. Simulation results were used to demonstrate of the proposed adaptive self-tuning decoupled control.

REFERENCES


