Novel Modeling and Control Strategies for a HVAC System

Including Carbon Dioxide Control

Abstract: Conventional heating, ventilating, and air conditioning (HVAC) systems have traditionally used the temperature and the humidity ratio as the quantitative indices of comfort in a room. Recently, the carbon dioxide (CO2) concentration has also been recognized as having an important contribution to room comfort. This paper presents the modeling of an augmented HVAC system including CO2 concentration, and its control strategies. Because the proposed augmented HVAC system is multi-input multi-output (MIMO) and has no relative degree problem, the dynamic extension algorithm can be employed; then, a feedback linearization technique is applied. A linear-quadratic regulator (LQR) is designed to optimize control performance and to stabilize the proposed HVAC system. Simulation results are provided to validate the proposed system model, as well as its linearized control system.

1. Introduction

HVAC systems are automatic systems that control temperature and humidity in buildings, providing people with a comfortable environment. The use of HVAC systems represents more than 50% of the world energy consumption [1–4]. Thus, balancing occupant comfort and energy efficiency is a main goal of HVAC control strategies.

In most previous studies, HVAC systems have been modeled considering only the temperature and the humidity ratio [5–8]. A nonlinear HVAC model that includes dynamics of temperature and humidity ratio is proposed in [5], which includes the design of an observer to estimate the thermal and moisture loads. In [6], an adaptive fuzzy output feedback controller is proposed, based on an observer for the HVAC system. In [7,8], a back-stepping controller and a decentralized nonlinear adaptive controller are respectively applied to the same model.

Recently, the CO2 concentration has been recognized as having an important contribution to room comfort [9,10]. Some researchers have proposed hybrid HVAC systems that represent the temperature and humidity ratio as continuous states and CO2 concentration as a discrete state [11,12]. However, because these states are strongly interrelated, it is more appropriate to integrate these continuous and discrete dynamics into a single model that includes temperature, humidity ratio, and CO2 concentration as states.

This paper presents a modeling and control strategy for a novel HVAC system that considers temperature, humidity ratio, and CO2 concentration. In the process of modeling, the dynamic extension algorithm of [13] is employed to deal with non-interacting control problem and no relative degree problem. After the dynamic extension process, a feedback linearization method can be applied to the proposed HVAC system to convert a bilinear system into a linear system. Linear controllers, pole placement and LQR can be designed for the linearized novel HVAC system to stabilize it and improve its control performance.

This paper is organized as follows: in Section 2, we present the bilinear model for the conventional HVAC system, including valve dynamics. Section 3 presents a novel HVAC system including CO2 concentration and its applicability in the feedback linearization method. Also, dynamic extension algorithm is applied for solving the no relative degree and interacting control problems in the MIMO system. In Section 4, we describe the design of linear controllers for the linearized HVAC system, such as pole placement and LQR controllers, to improve the system’s control performance and to verify the effectiveness of the proposed model.

2. Conventional HVAC System with Temperature and Humidity Ratio

As mentioned, conventional HVAC systems control only temperature and humidity. In this paper, we consider the single-zone system shown in Figure 1 as a representative conventional HVAC system. It consists of the following components: a heat exchanger; a chiller, which provides chilled water to the heat exchanger; a circulating air fan; the thermal space; connecting ductwork; dampers; and mixing air components [5]. The conventional HVAC system controls the temperature and humidity ratio as follows [5]:

・ Fresh air is introduced into the system and is mixed in a 25:75 ratio with recirculated air (position 5) at the flow mixer.

・ Second, air mixed at the flow mixer (position 1) enters the heat exchanger, where it is conditioned.

・ Third, the conditioned air is moved out of the heat exchanger; this air is ready to enter the thermal space, and is called supply air (position 2).

・ Fourth, the supply air enters the thermal space (position 3), where it offsets the sensible (actual heat) and latent (humidity) heat loads acting upon the system.

・ Finally, the air in the thermal space is drawn through a fan (position 4); 75% of this air is recirculated and the rest is exhausted from the system.

The control inputs for a conventional HVAC system are the flow rate of air, which is varied using a variable-speed fan (position 2), and the flow rate of water from the chiller to the heat exchanger. However, in our proposed HVAC system, the air recirculation rate (position 4) is added as a new control input, and some modifications are made to the basic operation rules listed above. That is to say, the 75% recirculation rate listed above in the first and last steps becomes a variable quantity, and is used as the third control input.

2.1. Mathematical Modeling of Conventional HVAC System

The conventional HVAC system is a model considering the temperature and the humidity ratio as states. The differential equations describing the dynamic behavior of the HVAC system in Figure 1 can be derived from energy conservation principles and are given by [5]:

The dynamic system given by Equation (1) can be converted into a state variable form for the purposes of control. Let ⍰⍰ ⍰ ⍰ and define the following parameters:

. Then, the dynamic equations given in Equation (1) can be written in the following state variable form.

The conventional HVAC system of Equation (2) is a 2-input, 2-output MIMO system: its inputs are the volumetric air flow rate and the chilled water flow rate, and its outputs are the temperature and the humidity ratio of the thermal space.

2.2. Adding Valve Dynamics to the Conventional HVAC Model

The Control input signals □ □ □□□□□□□ in the system described in Equation (2) are implemented using liquid valves. The valve dynamics can be modeled as follows in which □□s□ is the valve inherent characteristic and □□□□ is the flow rate of the liquid which enters the valve [14,15]:

By considering the characteristic of a linear valve as □□s□ □ □□□□□, the valve transfer function can be written as:

where □□, □□, □□, and □□ are the constant gains and the time constants, respectively; □ □ □□□□□□□ is the control signal applied to the actuator; and □ □ □□□□□□□ is the signal that is input to the HVAC system.

An augmented state space model with the new state vector, □ □ □□□□□□□□□□□□□ □ □□□□□□□□□□□□□ can be derived as

Thus, the system in Equation (5) represents a conventional HVAC system to which valve dynamics have been applied to implement the control signals. This conventional system can regulate only the temperature and the humidity ratio; other factors such as CO2 concentration, which affects the health of occupants or workers indoors, cannot be considered.

3. Novel Modeling of HVAC System including CO2 Concentration

If the recirculated air contains too much CO2, it can affect the health and work efficiency of the building’s occupants. Therefore, CO2 concentration should be one of the quantitative indices of room comfort, along with temperature and humidity ratio. In this paper, we propose an HVAC system that continuously controls all three of these indices.

From the mass balance equation, the average CO2 concentration □□ in the room can be represented as [14]:

where □□ □ □□ □ □□, □□ is the amount of CO2 generated in the room; □□ is the CO2 concentration in the inlet air; □□ is the CO2 concentration of air leaving the room, and □1 □ □□, 0 □ □ □ 1, is the air exchange rate.

3.1. Proposed HVAC System Model

The proposed HVAC system model includes CO2 concentration as a state. The differential Equation (6) can be integrated into the dynamic equations in (1). The valve dynamics of □□ are added to the control input vector □, and the control signal applied to the actuator of □□ also can be added to the actuator input vector □.

Let □□ □ 1, and let an augmented state vector

□ □ □x□x□x□. Then, the whole dynamics can be written in the state variable form as:

The novel HVAC system of (7) is a 3-input, 3-output MIMO system: its inputs are the volumetric air flow rate, the chilled water flow rate, and the outdoor air flow rate, and its outputs are the temperature, humidity ratio, and CO2 concentration of the thermal space. This proposed HVAC system can be linearized using a feedback linearization control method, as shown in Figure 2. Thus, we can finally obtain a linearized HVAC system that can be controlled using linear controllers.