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Heating, ventilation and air conditioning systems: Fault detection and isolation and safe parking

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ABSTRACT

This work presents an integrated framework for fault detection and isolation (FDI) and fault tolerant control (FTC) of variable air volume (VAV) boxes, a common component of heating, ventilation and air conditioning (HVAC) systems. To this end, first a statistical model based FDI framework is designed using existing techniques such as principal component analysis (PCA) and joint angle analysis as a benchmark for comparison. Then a novel linear causal model based framework for FDI of multiple actuator and multiple sensor faults is designed and implemented and shown to possess superior FDI capabilities compared to the statistical model based framework. Finally, a safe parking strategy is designed and the ensuing energy savings for the case of stuck dampers demonstrated.

1. Introduction

Government regulations and initiatives have placed a large emphasis on the reduction of energy consumption and increase in energy efficiency. Heating, ventilation, and air-conditioning (HVAC) systems are responsible for 40–50% of total building energy consumption, motivating research on energy efficient building control (see, e.g., Ma et al. (2012), Mendoza-Serrano and Chmielewski (2012, 2014), Cole et al. (2013, 2014), and Touretzky and Baldea (2014a,b)). It is estimated that in the U.S. alone (see e.g., Schein et al. (2006)), fault detection and isolation (FDI), and fault tolerant control methods could be capable of saving 10–40% of HVAC energy consumption.

These realizations have motivated significant research effort on devising FDI frameworks for HVAC systems with many studies focusing on air handling unit (AHUs) and variable air volume (VAV) boxes. Existing frameworks utilize a statistic based approach for the purpose of FDI. In House et al. (2001), a fault detection tool is proposed that uses a set of expert rules derived from mass and energy balances to detect faults in air handling units (AHUs). A subset of the expert rules which correspond to the current mode of operation are then evaluated to determine whether a fault exists. In Chen and Lan (2010), a PCA based approach is used to extract the correlation of measured variables in a heating/cooling building system and reduce the dimension of the measured data. Square prediction error (SPE) statistic is then used to detect sensor faults in the system. Then, a sensor validity index (SVI) is employed to identify the faulty sensor and a reconstruction algorithm is presented to recover the correct data for the faulty sensor in accordance with the correlations among system variables. In Du and Jin (2007), a combination of principal component analysis (PCA) and joint angle analysis are used to detect and isolate multiple faults in AHUs with variable air volume (VAV) boxes.

In Schein and House (2003), a fault detection method is developed for application to variable-air-volume (VAV) boxes using control charts. In Yoshida et al. (2001), a recursive autoregressive exogenous algorithm is used to develop a dynamic FDD model that addresses single fault scenarios in VAV boxes. In Wang and Qin (2005), a strategy using PCA is developed for detecting and validating flow sensor faults. The fault is detected using both the T^2 statistic and SPE and isolated using the SPE contribution plot. In Qin and Wang (2005), a hybrid approach utilizing expert rules, performance indexes and statistical process control models is used to address single fault scenarios in VAV boxes. In Du et al. (2007), a combination of PCA and joint angle analysis is used to diagnose sensor faults in VAV boxes. In Wu and Sun (2011), a cross-level fault detection methodology is proposed based on energy flow in HVAC systems that detects faulty HVAC units instead of component faults

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by comparing the current flow energy consumption in the system with respect to its normal expected patterns. The existing results in the literature, however, consider only isolation of single fault scenarios in the VAV boxes and do not consider multiple sensor faults or multiple actuator faults in the VAV boxes, in part due to the limitation of the underlying statistical based approaches (as demonstrated via simulations in the present manuscript).

In the area of dynamic model based FDI, there is a large body of methods in the literature utilizing linear model based FDI design, and these approaches can be categorized into parity relation and diagnostic observer (see e.g., Frank (1990), Venkatasubramanian et al. (2003) and Magni and Mouyon (1994)). Note that these methodologies are equivalent when it comes to residuals generation and both use output estimation error for defining residuals (see e.g., Gertler and Monajemy (1995) and Yoon and MacGregor (2000)). However, these methods have not been utilized to detect and isolate actuator faults where the effect of the fault is compensated by the controller. Thus, the area of FDI using linear models in general, and applications to HVAC systems in particular, stands to gain from novel linear model based FDI design that achieve FDI for sensor and actuator faults (including those masked by the controller).

There also exist results on fault tolerant control (FTC) of HVAC systems. In Seem (2001), the control design compensates for the effect of faults as much as possible by switching between different control modes available in the air handling unit design. In Hao et al. (2005), single sensor faults are diagnosed and handled via sensor redundancy. In Talukdar and Patra (2010), a model based fault tolerant control strategy is developed for handling multiple stuck dampers in the VAV boxes of HVAC systems. Fault tolerant control is achieved by modifying the airflow through the healthy zones. This is based on the assumption that the overall HVAC system maintains a constant total air flow rate. Under this assumption, changing the amount of air flow entering the healthy zones affects the amount of air flow rate entering faulty zones. This assumption, however breaks down in applications where the static pressure is held constant. In Bengea et al. (2015), the fault tolerant control design of the HVAC system is based on real time estimation of the fault magnitude, and determining MPC constraints (input constraints) based on those values.

These fault-tolerant control approaches, however, are all predicated on the idea of maintaining nominal operation as the only control objective before and after fault occurrence, which might simply be impossible, or expensive in case of certain faults. Recently, safe-parking based approaches for fault-tolerant control have been proposed (see e.g., Gandhi and Mhaskar (2008) and Du and Mhaskar (2011)) that upon fault detection, prescribe temporarily operating (or 'parking') the process at an appropriate operating point, instead of trying to maintain nominal operation. Various algorithms for safe-parking have been proposed focusing on stability/optimality of the overall operation. These ideas, however, have not been applied to HVAC systems. In summary the area of VAV control stands to benefit from implementations that can handle multiple actuator and sensor fault detection and isolation, and implement safe parking based approaches.

Motivated by the above considerations, in this work, we design and implement an integrated framework for fault diagnosis and safe parking of VAV boxes of HVAC systems. To compare with existing approaches, first, a statistical model based FDI scheme is designed using existing PCA and joint angle analysis based techniques. Then we design linear causal model based frameworks for detection and isolation of multiple actuators and multiple sensor faults. The linear model is identified using a subspace identification method applied to data from a detailed Modelica model of an AHU with five VAV boxes. The linear model based approach is seen to possess superior fault-isolation capabilities. Finally, the problem of fault handling in the context of VAV boxes is addressed, recognizing that while in the present context, the faults are not safety critical in nature, they do present an opportunity for trading off between comfort and energy usage. Thus, a safe parking strategy is designed to handle stuck dampers and the resulting energy reduction demonstrated.

2. Preliminaries

In this section, we briefly review the air handling unit (AHU) model first, then describe the VAV box model.

2.1. Air handling unit model

An air handling unit usually comprises fans, heating and cooling coils, and dampers to achieve the supply air temperature set point. To serve as a simulation test bed, we use a detailed Modelica model of an AHU with five VAV boxes. The testbed AHU model has three dampers (outdoor, recirculation, and exhaust), cooling and heating coils with valves and temperature, pressure and flow sensors for monitoring and control. Each of the actuators in the AHU model is controlled using a single loop proportional integrator (PI) controller. The control objective is to provide supply air with a constant temperature (typically 55 °F) at the downstream of the supply fan. The supply fan is used to maintain the static pressure in the supply duct at a constant value. Fig. 1 shows a schematic diagram of a typical AHU.

The testbed AHU system has four modes of operation used for controlling the supply air temperature. A sequencing logic determines the mode of operation. In the heating mode, the heating coil valve is the active actuator and is modulated to maintain the supply air temperature at set point and the AHU dampers are controlled to allow the minimum outdoor air needed to satisfy the ventilation requirements. When the cooling load increases, the system simply mixes outdoor (cold) air and returns air to achieve the set point with both heating and cooling coil valves being closed. The mode of operation changes to mechanical cooling when the outdoor air is too warm to achieve the supply air temperature set points. In this mode, the cooling coil valve is manipulated to meet the supply air temperature set point. If the outdoor air temperature is less than a certain value (typically 65 °F) the outdoor air damper is kept fully open. If the outdoor air temperature is greater than the selected value, mechanical cooling is continued with the minimum outdoor air required for ventilation. The conditioned supply air is distributed to the five zones. Each zone has a variable-air-volume (VAV) box with hydronic reheat. In the next section, we describe the control structure in the VAV boxes.

2.1.1. VAV boxes

Fig. 2 shows a schematic diagram of a zone VAV box and the corresponding sensors in the model. The VAV box uses a damper to modulate the amount of air entering the zone, and the hydronic coil to reheat the air entering the zone when necessary. The thermostat and flow sensor measure the air temperature in the zone and the flow rate of air into the zone. A discharge air temperature sensor measures the temperature of the air stream entering the zone (see Schein and House (2003) for more details on the control structure of VAV boxes).

The control structure for VAV boxes is based on two different control loops for cooling and heating, respectively. In the cooling mode, a cascade control loop is implemented. The outer loop has the zone temperature as the controlled variable and the set point for air flow rate to the room as the manipulated variable. In the inner loop, the damper is modulated to reach the desired set point for flow rate. In the heating mode, the air flow rate to the room model