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Energy efficient model based algorithm for control of building HVAC systems

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ABSTRACT

Energy efficient designs are receiving increasing attention in various fields of engineering. Heating ventilation and air conditioning (HVAC) control system designs involve improved energy usage with an acceptable relaxation in thermal comfort. In this paper, real time data from *a* building HVAC system provided by BuildingLAB is considered. A resistor–capacitor (RC) framework for representing thermal dynamics of the building is estimated using particle swarm optimization (PSO) algorithm. With objective costs as thermal comfort (deviation of room temperature from required temperature) and energy measure (E_{cm}) explicit MPC design for this building model is executed based on its state space representation of the supply water temperature (input)/room temperature (output) dynamics. The controllers are subjected to servo tracking and external disturbance (ambient temperature) is provided from the real time data during closed loop control. The control strategies are ported on a PIC32mx series microcontroller platform. The building model is implemented in MATLAB and hardware in loop (HIL) testing of the strategies is executed over a USB port. Results indicate that compared to traditional proportional integral (PI) controllers, the explicit MPC's improve both energy efficiency and thermal comfort significantly

1. Introduction

Energy influences the society not only from its usage but also in the form of pollution created by its production source. Though clean energy is the effective alternative, the infrastructure cost and technology maturity are hindering its immediate acceptance in the developing countries. Drive to increase the energy efficiency in end usage devices can reduce the quantum of energy required. It can also meet its increased demand created by the increasing penetration of industries and consumers across the world.

Optimal energy usage is being advocated in various fields including manufacturing, transport, building automation systems etc. The heating ventilation and air conditioning (HVAC) system, is a major contributor to energy consumption in the various systems that form the building automation systems (Pérez-Lombard et al., 2008). Considering its high degree of penetration in both developed and developing nations, the demand for energy by HVAC systems is on the rise with every progressing year.

Usage of energy in commercial and residential buildings is being improved in various stages of construction (Wong and Li, 2010). Using construction techniques that allow easier draft of outside air, thermal comfort is improved (Han et al., 2009; Haase and Amato, 2009; Zhai et al., 2011; Yin et al., 2010 and Luo et al., 2007). Such methods reduce the load on the HVAC systems considerably. However, the HVAC systems provide *a* great scope for improvement in terms of efficient energy usage in its operation.

One method of optimization carried out in such systems includes component selection and redesign during manufacturing (Dawson-Haggerty et al., 2010). However, this method is better suited for new installations in public buildings and homes, since a replacement of entire system in existing buildings with such improved components will involve an increased capital investment. Control strategies ranging from the open loop heating curve (Široký et al., 2011) to closed loop decoupled proportional integral (PI) controllers (Stemmann and Rantzer, 2014; Salsbury, 2005; Dounis and Caraiscos, 2009; Peffer et al., 2011) and advanced model based control strategies (Karlsson and Hagentoft, 2011; Ma et al., 2009; Yuan and Perez, 2006; Paris et al., 2010; Kolokotsa et al., 2009; Privara et al., 2011) have been reported.

Traditional control strategies (heating curve, decoupled PI) are predominantly tuned based on the user knowledge and are focused mainly on closed loop stability. Model based control

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strategies improve optimal usage of energy and also ensures thermal comfort (Bénard et al., 1992; Kummert et al., 2001). Supervisory scheduling mechanisms impart control driven by cost per unit of energy by lean operation during peak times (Hazyuk et al., 2012a,b).

Such advanced strategies provide wide opportunities in improving the design of overall systems that improve energy efficiency of systems based on optimal cost per unit of energy consumed. However, control strategies that can optimize existing HVAC systems with no additional components also become important since their life can extend into another decade, assuming that all HVAC systems are designed more efficient henceforth.

Superheat (SH), provided in Eq. (1) determines the addition or removal of heat in the controlled environment (Vinther et al., 2013). Since pressure provides a lag free inference to refrigerant temperature as compared to measuring temperature directly, an inferential measurement of temperature is preferred. However, this measurement is mainly used as *a* safety mechanism (using electronic expansion valves) in preventing incompressible liquid refrigerant from entering compressor (Elliott and Rasmussen, 2010; Finn and Doyle, 2000; Schurt et al., 2009).

$$SH = f(P_{Ein}) - f(P_{Eout}) \quad (1)$$

where, P_{Ein} is the refrigerant pressure at the inlet of the evaporator and P_{Eout} is the refrigerant pressure at the inlet of the compressor.

In large commercial buildings, though the refrigeration cycle is used in heating or cooling the working fluid (water), control of temperature of this water is based only on optimization of thermal comfort. The novelty reported in this paper is the usage of temperature difference between supply/return water temperatures in optimal model based control design.

In this paper, a resistor–capacitor (RC) based model of a public building provided in (Cigler et al., 2013) was used to simulate a building (with interacting north/south blocks) on which testing of control strategies was carried out. Using ambient temperature, supply/return water temperatures and room temperature data, the RC parameters of the model were estimated using particle swarm optimization (PSO) algorithm. A traditional decentralized PI controller based on ideal relay feedback (IDR) technique was designed. Also, an explicit multi parametric model predictive controller (mpMPC) with thermal comfort as the optimization cost was designed. Another mpMPC with the temperature difference between the supply and return water temperatures called the superheat mpMPC (mpMPCSH) was designed. The resulting controllers were implemented on an embedded platform using a PIC32mx795H512L and hardware in loop (HIL) simulation of the strategies were carried out. The HIL scheme is depicted in Fig. 1. The controllers were compared based on energy consumption measure (E_{cm}) and also thermal comfort during servo tracking HIL tests on the estimated building model implemented in MATLAB using serial communication. Hence, a control strategy aimed at greener climate control in buildings is reported.

The paper is organized as follows, Section 2 discusses the PSO based estimation of model parameters from closed loop data while Section 3 discusses the design of controllers which include relay tuning feedback based decentralized PI controllers; design of mpMPC based on thermal comfort and also mpMPCSH. In Section 4, quantitative and visual comparison based results from HIL test of different control strategies are discussed. Conclusions are drawn in Section 5.

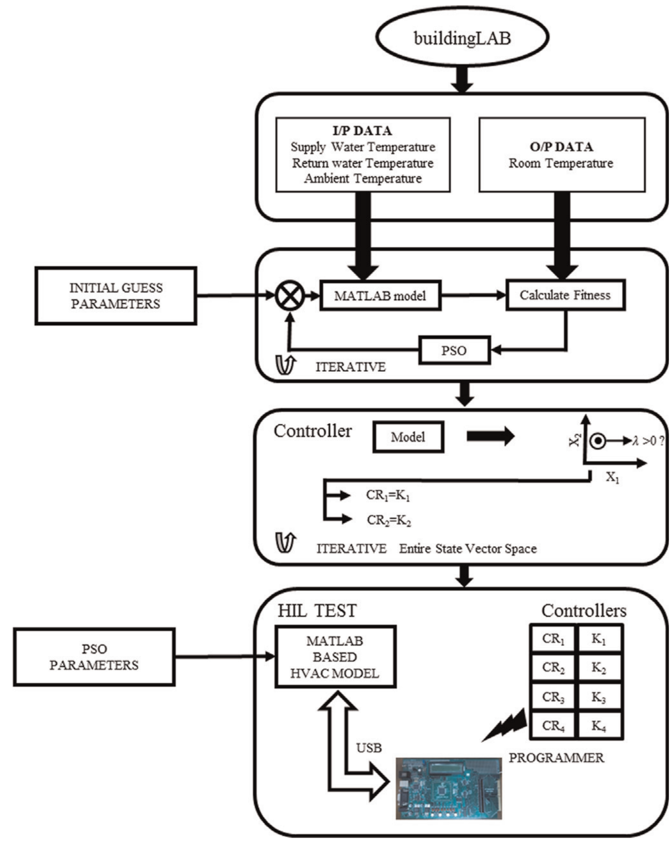

Fig. 1. Sequential design of controller for building HVAC system.

2. Estimation

2.1. Resistor–capacitor building model

Model based control strategies are based on a sound mathematical model of the given system to be controlled. Obtaining such model from the process also demands expertise of the system itself. This only improves the validity of any control solution to the given system. The advent of modeling of HVAC systems has led to standardization of certain tools which are used in understanding and designing of controllers for HVAC systems. A few of them include DOE-2, ESP-r, TRANSYS, Energyplus, eQUEST, HVACSIM+ etc. (Trčka and Hensen, 2010), which are based on energy/mass balance equations resulting in higher order complex physical models. Design and implementation of control laws for such models also involve high degree of complexity. Based on dynamic data sets that can be obtained from building management systems, it is possible to model the data into a more generic, yet complex black box models. Such designs become very specific and hence control design process itself will require longer tenure.

Simpler lumped parameter models representing building thermal dynamics have been reported. In the absence of exhaustive building information in terms of thermal dynamics or physics, linearized resistor–capacitor (RC) representation approximately represents the same. Here, resistance is the heat transfer by conduction/convection at the surface of the wall and the capacitance is the heat capacity of the building (Ramallo-González et al., 2013). Such modeling also called component based system modeling, describes the system in hand as a set of first-order equations. The building model that is used in this paper is one such system constituting of a set of first-order differential equations provided in Eq. (2) (Cigler. et al., 2013).