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Iterative Learning Control for Coupled Temperature and Humidity in Buildings

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Abstract:
This paper presents the design of a passivity-based iterative learning control (ILC) algorithm for coupled temperature and humidity in buildings. Since buildings are subjected to repeating diurnal patterns of disturbances, ILC algorithms can significantly improve performance. Moreover, since it is a feedforward control scheme, it can be used in conjunction with either model-free or model-based approaches such as the popular model predictive control techniques. However, model-based control is challenging for buildings because of the difficulty in identifying building thermohygrometric models. Furthermore, the control law should be designed in such a way as to address both temperature and humidity set points. We propose a model-free ILC design approach facilitated by the inherent passivity of building thermohygrometric dynamics. We first demonstrate that the building dynamics are strictly output-incremental passive. This property is then exploited to design ILC laws that guarantee convergence in the iteration domain, while being robust to model uncertainty. Since we wish to control both temperature and humidity using only one input - mass flow rate of supply air, convergence to a point is not guaranteed; instead convergence to an ellipse on the temperature-humidity plane is shown. The controller performance is demonstrated through simulation examples.

Keywords: Temperature, humidity, passivity-based control, iterative learning control, building automation, human comfort.

1. INTRODUCTION

Thermal management in buildings has emerged as a popular research area given the large energy footprint of heating, ventilation, and air conditioning (HVAC) systems in buildings. Typical controllers in practice tend to be unsophisticated (PID or bang-bang), leaving substantial room for improvement in both energy consumption and human comfort. These controllers do not inherently include energy optimization, and fail to explicitly consider predictable disturbances. Because of this, researchers have investigated more advanced control strategies for thermal management in buildings.

Though extensive work has been done on indoor environment control over the years, most of the previous studies have tackled temperature regulation alone, ignoring humidity when modeling energy transfer and designing control architectures (Shaikh et al., 2014). Nonetheless, temperature and relative humidity are two of the primary factors that affect human thermal comfort (Damle et al., 2012). Both temperature and humidity can be measured in real-time by inexpensive sensors and ambient forecasts for them can be predicted reasonably well many hours in advance. Studies have also shown that human occupants are comfortable within a region of the temperature-humidity plane, thus it is not necessary to achieve specific set-points for both temperature and humidity. Instead, it is sufficient to control the temperature and humidity into a comfort zone. Comfort zone set-based control in buildings has been introduced in our previous work (Okaeme et al., 2016).

The majority of current work in building thermal control employs model-based design including model predictive control (MPC) (Sturzenegger et al., 2016; Borrelli et al., 2012; Oldewurtel et al., 2012). MPC lends itself well to building thermal control, since future disturbances can be predicted and energy optimization capabilities are built-in. However, such model-based schemes require accurate models, thus the performance of predictive controllers can diminish significantly as model uncertainty is introduced. Building models can be difficult to accurately identify, due to vast differences in construction materials and architecture among buildings, as well as the time-varying nature of building thermal dynamics. This motivates the search for a model-independent solution.

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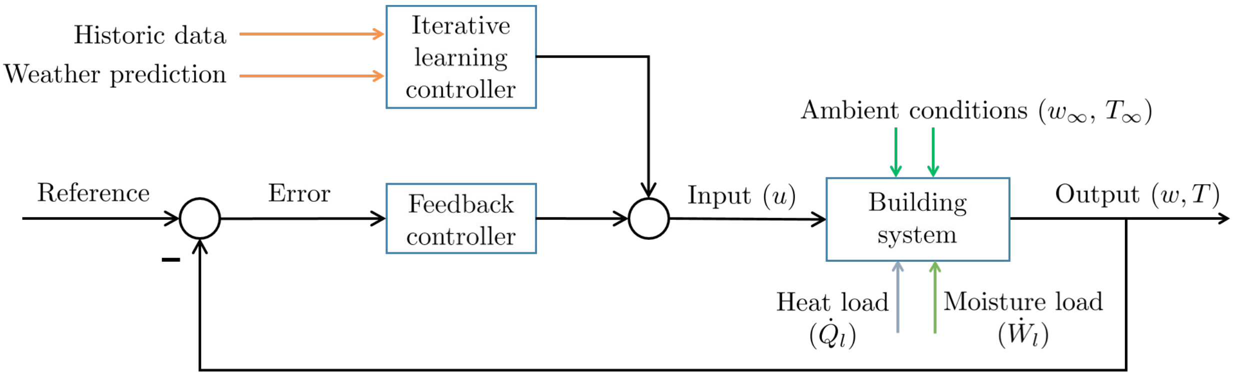

Fig. 1. Problem description - temperature T and humidity ratio w are to be maintained within a desired set throughout a 24-hour iteration, facilitated by combined proportional feedback and ILC feedforward.

On the other hand, feedforward control can improve transient performance as well as reject known disturbances. Iterative Learning Control (ILC) is a common strategy for tuning feedforward signals in systems that are subject to a periodically repeating disturbance and return to the same initial conditions to begin each subsequent iteration. Our prior work in (Minakais et al., 2014) presented an ILC approach to building temperature control and demonstrated improved setpoint tracking. A few other ILC applications to buildings have been reported in the literature (Lautenschlager and Lichtenberg, 2016; Peng et al., 2016). To the best of the authors' knowledge, however, there is no prior research on ILC algorithms for regulating both temperature and humidity. In this work, we present an ILC strategy for regulating both parameters within a thermal comfort zone set as recommended by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE, 2010). This method does not require specific model information, and is shown to result in set-convergence based on the inherent passivity of the thermohygrometric dynamics of the building.

It is key to note that in this work we make the assumption that disturbances are perfectly repeated to facilitate the ILC approach. While this assumption does not hold in practice, we can utilize a historical database of weather data to find 24-hour iterations of disturbances that do repeat (not necessarily on consecutive days).

The rest of the paper is organized as follows: Section 2 discusses the problem scope and solution strategy; Section 3 introduces the building model and provides passivity analysis of the closed-loop system; Section 4 discusses the design of ILC parameters, including a stability proof and analysis of the steady-state convergence; Section 5 shows simulation results and Section 6 is the paper conclusion.

2. PROBLEM DESCRIPTION

A typical closed loop building control system is shown in the block diagram above (Fig. 1). The system dynamics are affected by internal disturbances such as moisture/heat loads $\dot{W}_l$(kg/s), $\dot{Q}_l$(W) from occupants, equipment, etc. as well as environmental weather conditions such as ambient temperature T_∞(K) and ambient humidity w_∞. The control input u_i(kg/s) to the system is the supply air mass flow rate and the outputs of interest are the humidity ratio w_i and temperature T_i(K) for the i^{th} zone. We wish to drive the temperature and humidity ratio of each zone to lie within a comfort set, chosen here as an approximation of the comfort zone recommended by ASHRAE (Fig. 2). The ILC algorithm uses information from historical data, weather prediction and sensor measurements to achieve the control objective.

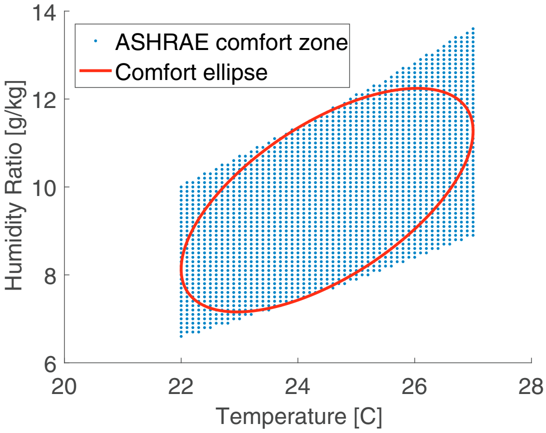

Fig. 2. Comfort ellipse estimated as a subset of typical human comfort zone determined by ASHRAE.

2.1 Solution Strategy

We utilize a combination of proportional feedback control and feedforward ILC for thermohygrometric regulation. The purpose of the feedforward term is to eliminate steady state error and reject disturbances caused by repeated ambient conditions. Since the entire feedforward input is computed prior to each upcoming day, errors in weather prediction can negatively affect performance. This is resolved by the feedback controller, which can correct these subtle uncertainties as they arise. Note that since mass flow rate is the single control input (per building zone) for both temperature and humidity, we expect the ILC solution to converge to a set in steady state, rather than a point. Thus the control strategy is to choose desired setpoints for zonal temperature and humidity such that the steady state set for each zone lies entirely within the comfort zone ellipse shown in Fig. 2.