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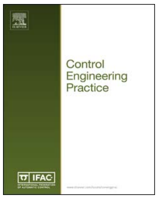

Prioritised objectives for model predictive control of building heating systems

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ABSTRACT

Advantages of Model Predictive Control (MPC) strategies for control of building energy systems have been widely reported. A key requirement for successful realisation of such approaches is that strategies are formulated in such a way as to be easily adapted to fit a wide range of buildings with little commissioning effort. This paper introduces an MPC-based building heating strategy, whereby the (typically competing) objectives of energy and thermal comfort are optimised in a prioritised manner. The need for balancing weights in an objective function is eliminated, simplifying the design of the strategy. The problem is further divided into supply and demand problems, separating a high order linear optimisation from a low order nonlinear optimisation. The performance of the formulation is demonstrated in a simulation platform, which is trained to replicate the thermal dynamics of a real building using data taken from the building.

1. Introduction

The building energy sector has been widely recognised as a significant contributor to global energy consumption and as such, the effects of human influenced climate change. Globally, as much as 20–40% of total energy usage is consumed in buildings (Pérez-Lombard, Ortiz, & Pout, 2008), while in Key (2014), it is stated that the services and households sector was responsible for 35% of global energy consumption in 2012. Consequently, the sector accounts for 30% of CO_2 emissions (Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2014). While the need for large scale improvements is clear and stricter building regulations have encouraged better insulation and more efficient equipment, it is shown in Peeters, Van der Veken, Hens, Helsen, and D'haeseleer (2008) that typically, modern heating systems are not used efficiently and are not adjusted to meet the needs of changing conditions.

Traditional building heating systems tend to be controlled to react to current system and environmental conditions. Due to the slow nature of the thermal dynamics associated with a building, such an approach can lead to inefficient operation and excess energy use. A promising and commonly cited alternative to current strategies is Model Predictive Control (MPC), the literature for which has been widely covered (Liao & Dexter, 2010; Ma et al., 2012; O'Dwyer et al., 2014; Oldewurtel et al., 2014). By predicting the future state trajectory of a system and determining the optimum input sequence, MPC can account for varying heat demands in a building due to changing weather (Lazos, Sproul, & Kay, 2014) and occupant usage (Klein et al., 2012; Oldewurtel, Sturzenegger, & Morari, 2013) before the changes occur.

While MPC has been shown to outperform typical rule-based strategies in terms of thermal and energy performance (Shaikh et al., 2014; Sturzenegger, Gyalistras, Morari, & Smith, 2015), the potentially large number of zones in a typical building may result in a complicated objective with many, often competing, goals (Yang & Wang, 2012). A strategy may often seek to optimise some comfort metric in all occupied zones for example, while using as little energy as possible. If improving the comfort within a zone requires more energy, some balance must be assigned to dictate an acceptable trade-off between energy savings and comfort satisfaction. This balance is dependent on the thermal dynamics of each individual zone (O'Dwyer et al., 2015). Consideration of all zones in a single objective requires the appropriate selection of many tuning parameters.

In this paper a prioritised formulation is introduced which seeks to achieve improved comfort and energy performance allied to a level of

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scalability and flexibility which would allow it to be commissioned and reconfigured without the need for an intricate system-specific parameter selection process. A lexicographic formulation is developed to handle the competing objectives of comfort and energy. The satisfaction of comfort criteria in all zones is first established, followed by a minimisation of the energy required to achieve the optimised comfort level. Furthermore, it is shown that in the case of faults, using such a strategy allows for objectives associated with individual zones to be removed from the formulation without the need for reassigning weights in the objective.

An additional optimisation layer in the control hierarchy is then introduced to enable nonlinearities associated with the heating system to be included separately to the high-order linear lexicographic problem. The overall formulation then consists of three layers of optimisation. The first and second are linear and quadratic programs respectively with a potentially high number of variables and constraints (related to the product of the number of zones in the building and the length of the prediction horizon). The final layer is a nonlinear optimisation problem with a lower number of variables and constraints (proportional to the prediction horizon).

To assess the performance of the strategy, a simulation platform is developed based on an RC-network analogy commonly used in building modelling. Using a validated platform in place of a real building allows for the analysis and comparison of different strategies with consistent external conditions. The parameters of the simulation model are calibrated using a metaheuristic optimisation algorithm so that the thermal dynamics of the simulation platform replicate those of a real building. This is achieved using measured data from the building. To account for unmeasured disturbances and the corrupting impact they might have on the identification process, a disturbance estimation method is used based on a spatial filtering process using Principal Component Analysis (PCA). Low-order zone models are then derived from the measured building data for use within the control formulation, once again incorporating the disturbance estimation techniques.

The prioritised MPC formulation is implemented in the simulation platform and compared in terms of energy consumption and thermal comfort with the weather compensation strategy which is currently employed for this building. It is then shown how the strategy can be adjusted to reduce energy at the expense of comfort by the end user. The adjustment is tangible in nature as it only concerns acceptable widths of zone temperature comfort bands (in ° C). Finally, it is shown that a fault in one zone of the system does not affect the control of the remaining zones if the fault is accounted for in the prediction models. All results are obtained in simulation.

In Section 2, a prioritised-objective formulation is outlined, separating the objectives of energy and comfort. The reconfigurability of the formulation in the event of faults is also demonstrated. Section 3 considers the issue of incorporating nonlinear heating equipment in a strategy with a large number of variables and constraints. In Section 4, the full set of constraints and objectives for each level of the control hierarchy is derived. The performance of the strategy is assessed in Section 5, using a simulation platform, developed to represent the thermodynamic properties of a real building, using measured data from the building.

2. Control

2.1. Background

The performance objectives of foremost importance to any building heating (or cooling) system control strategy could be separated into two main categories: reduction of energy consumption and satisfaction of the occupant's comfort demands (Castilla et al., 2011). The former objective is the more conceptually unambiguous, typically consisting of a cost in terms of units of energy (Liao & Dexter, 2010; Sturzenegger et al., 2015) or units of currency (Oldewurtel et al., 2010; Ma et al., 2012).

The comfort objective can be somewhat more abstract. Crucially, the notion of *comfort satisfaction* in a general sense is subjective to each individual occupant. A commonly used index for quantifying comfort is the Predicted Mean Vote (PMV) which is used for predictive control purposes in Ferreira, Ruano, Silva, and Conceição (2012) and Freire, Oliveira, and Mendes (2008). Limitations associated with the use of PMV are outlined in Humphreys and Fergus Nicol (2002) in which it is noted that in surveys of individual buildings, the actual observed mean vote often does not correspond to calculated values. Furthermore, as the PMV model is nonlinear and quite complicated, it may be more suited to model-free approaches. For many strategies (Shaikh et al., 2014), particularly those for which humidity control is not available (as is the case for the hydronic heating system studied here), a comfort cost based on the deviation of the zone temperature from a given set-point is used. For the remainder of this chapter, *comfort* is defined by the proximity of a zone temperature to its set-point.

In typical MPC formulations, a state-space structure is used for the optimisation model, with a constrained numerical optimisation employed to determine the future control sequence (Camacho & Alba, 2007; Maciejowski, 2002). The cost function at the kth sample is often of the form:

$$J(k) = \sum_{i=1}^{H} \|\hat{z}(k+i) - r(k+i)\|_{Q}^{2} + \sum_{i=0}^{H-1} \|\Delta\hat{u}(k+i)\|_{\mathcal{R}}^{2} \quad (1)$$

where $\hat{z}(k+i)$ is the output predicted for i steps in the future, $r(k+i)$ is some desired reference, and $\hat{u}(k+i)$ is the predicted input, using a H-step prediction horizon.

This objective is formulated so as to minimise the deviation between the plant and the reference, with the control increment included to introduce integral action to the formulation (Maciejowski, 2002). The reasoning behind this standard cost function does not however naturally extend to the problem of building heating systems. Building energy control typically seeks to minimise the deviation of the outputs (the zone temperatures) from a reference, while also minimising the sum of the inputs (or squared inputs) to reduce energy supplied to the building, as opposed to the sum of the input increments:

$$J(k) = \sum_{i=1}^{H} \|\hat{z}(k+i) - r(k+i)\|_{Q}^{2} + \sum_{i=0}^{H-1} \|\hat{u}(k+i)\|_{\mathcal{R}}^{2} \quad (2)$$

Variations of this cost formulation can be seen in the building energy literature (Chandan & Alleyne, 2013, 2014). By the nature of the problem, as energy is often required to improve comfort, the twin objectives of set-point tracking and input reduction will tend to oppose each-other. The result of this will be a cost function that attempts to strike a balance between comfort and energy, the bias of which will dependent on how the function is weighted. This is a subjective problem which will vary with the preference of the user and the specifics of the models used. A strategy in which a non-trivial tuning procedure is required for each building in which the strategy is used is far from ideal.

A common strategy employed to avoid the inclusion of contradicting objectives in a single cost function is to use an economic MPC formulation where only the energy supplied is minimised (Hazyuk, Ghiaus, & Penhouet, 2012b; Oldewurtel et al., 2013; Sturzenegger et al., 2015). By minimising the energy cost as opposed to the squared energy cost, this form is more intuitively appealing. Often the zone temperatures are included in the constraints rather than in the cost