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LH/Cigler13/2013

07/08/2013

Review by Lieve Helsen, KU Leuven (Belgium)

To what extent the subject of the thesis is relevant to current needs of the scientific community
Today a lot of effort is put in research concerning the development of MPC of HVAC systems in buildings. However most of the research work is simulation based (no validation by cases) and rather academic in nature (no model mismatch, perfect prediction ...). The current PhD thesis copes with these two aspects:

1. By MPC implementation in real cases (up to 3 cases!) the real MPC performance can be evaluated and practical problems can be identified.
2. By taking model mismatch and disturbance prediction uncertainties into account the MPC strategy is made much more robust.

Furthermore the assessment of thermal comfort has been improved by using PMV instead of the operative temperature. Translation into a QP problem was needed to allow longer prediction horizons, which was shown to be necessary.
This work can thus be classified as very relevant to current needs of the scientific community.

To what extent the main objectives of the work have been fulfilled
The main objectives of the work are defined as:

1. Evaluation of MPC energy saving potential on a real building
2. Development of an MPC formulation less sensitive to model mismatch and prediction errors
3. Development of a computationally tractable PMV based MPC

The candidate has fulfilled all these objectives, and even more, the related work is all published in four peer reviewed international papers (paper 1 and paper 2 for objective 1, paper 4 for objective 2 and paper 3 for objective 3), which means that the work has been reviewed and approved by international experts within the field. The published work scores high in both quality and quantity. The candidate has been able to obtain both practical and theoretical achievements in a rather short time frame of 4 years.

To what extent the methods used in the thesis have been appropriate
The PhD candidate presents a very good overview of the current state-of-the-art and discusses the methods used by other researchers in a critical way. Based on this critical study the candidate proposes some alternative methods, always taking practical aspects into account, and combining several disciplines (system and control engineering, optimization, software architecture ...). Moreover, monitored data and detailed building simulation models are used, which requires knowledge and insight from a completely different discipline. A question that pops up: how is the structure of the reduced order controller model chosen, where is it based on?

What the main results and contributions of the work are
The main results can be classified in practical and theoretical achievements:

- Practical achievements
  I would like to stress that these practical achievements are far from easy to reach, are unique and present a high added value to the work.
  a. Implementation of MPC on a pilot building of the CTU in Prague, showing energy saving potential and peak energy demand reduction.
  b. Besides the CTU building in Prague, two additional cases have been studied: new office building in Munich (Germany) and new office building in Hasselt (Belgium).
  c. Development of the BuildingLab tool to make the MPC strategy more understandable and to investigate MPC performance (illustrative and educative aims)

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- Theoretical achievements
  a. Alternative MPC problem formulation that achieves better control performance in situations when there are model mismatch and disturbance prediction errors.
  b. Proposal (not yet tested since the appropriate sensors were not available, however accuracy analysis was performed) of a tractable method for solving PMV based MPC problems, by translating the original general constrained optimization problem into a quadratic programming problem that can be solved in polynomial time.

  The proposed algorithms and techniques have been demonstrated and tested on several case studies (CTU building, Munich building, Hasselt building), or analyzed based on simulations using a 2-zone office building in TRNSYS.

To what extent the work is important for the further development of science
Both the practical and theoretical achievements present a huge step forward in the development of science.
Theoretical achievements:

- By incorporating model mismatch and disturbance prediction uncertainties the MPC strategy moves a step further from theory towards practice. Besides this increase in robustness leading to better performance, the alternative MPC formulation:
  - is not oscillatory due to smoothing terms introduced in the cost function,
  - guarantees recursive feasibility of the optimization problem,
  - respects user-defined comfort limits in such a way that it is highly probable that high comfort violations do not occur,
  - does not increase significantly the energy consumption,
  - does not increase the numerical complexity of the problem significantly,
  - is able to capture small and high comfort violations, thereby ensuring that high comfort violations do not occur at any cost

  A lot of practical aspects are thus accounted for, at the cost of only one additional tuning parameter.
- The general PMV-based MPC formulation is non-linear and as such not scalable. In this work a computationally tractable approximation of the nonlinear optimal control problem is presented and its accuracy is analyzed. This allows using PMV-based MPC also for longer prediction horizons, for which the necessity was shown. Nonlinear solvers are no longer needed.

Practical achievements:

- Real cases allow to verify and to validate methods and strategies developed, an aspect that is often lacking in simulation based research work. These real cases present a high added value by translating theory into practice. As such the strengths and weaknesses of the methodologies developed are known, and points of attention for product commercialization can be defined.
- The BuildingLab tool can contribute to a larger playing field for MPC in buildings, eliminating some of the bottlenecks (e.g. poor understanding by operators) for widespread market implementation.

Whether the thesis satisfies conditions of a creative scientific work
This work is very multidisciplinary, integrating the disciplines of system and control engineering, optimization, software architecture, thermal systems and building physics. This integration is on itself a great contribution and adds a significant step forward to the current knowledge. Translation of system and control theory to the application of HVAC in buildings is not that straightforward. The number of

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possible approaches is very large and not all of them are suitable for this type of applications. Therefore, a careful and scientifically sound selection is crucial, being aware of the benefits and drawbacks of each method applied, and taking practical issues into account to end up with a viable solution. The candidate has performed this integration and translation in a solid way, leading to innovative and creative work. The combination of thorough theoretical work and application to cases is an additional strength of this research work.

My conclusion:

The author of the thesis proved to have an ability to perform research and to achieve scientific results. I do recommend the thesis for presentation with the aim of receiving the Degree of PhD.

Line Helsen
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