Intelligent Control System Design for Energy Conservation in Commercial Buildings

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A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

February 22, 2016

Abstract

This thesis focuses on the development of model predictive control (MPC) strategies for reducing energy consumption in air-conditioned buildings. It is well known that the building sector is responsible for 40 per cent of the world's energy usage and 33 per cent of all greenhouse emissions. As a result of global environmental issues and decreasing energy resources, there is strong motivation to develop more efficient control strategies for Heating, Ventilation, and Air Conditioning (HVAC) systems in buildings. The existing HVAC control strategies are not energy or cost efficient, which results in energy waste, high on-peak electricity demand and poor thermal comfort in buildings.

Previous works have shown that MPC can be utilised as a supervisory controller to achieve energy saving while maintaining the indoor thermal comfort in buildings. However, most of the past studies were focused on small residential buildings or mid-size commercial buildings. It is highly desired to improve the existing MPC strategies to make them more reliable and applicable for large commercial buildings. This thesis extends the previous works by addressing the following challenges when dealing with the large buildings. Firstly, HVAC plants and the thermal dynamics of buildings are inherently nonlinear. Accurate modelling of these components is difficult due to the limited number of sensors that are usually installed and the paucity of prior knowledge of the system. There is a need to develop models that are capable of effectively handling the nonlinearity to achieve better modelling accuracy. Secondly, in large commercial buildings with adjacent large open spaces, the effects of thermal coupling between differently

controlled spaces play a crucial role. This significance of the interaction between zones has seldom been discussed before and requires more thorough investigation. Thirdly, although load shifting function of MPC have been proven to be effective in achieving cost savings in buildings with a considerable thermal mass, it is demanding to investigate the application value of these strategies in lightweight commercial buildings. Finally, given the presence of uncertainties, these models may not be able to predict the indoor temperature accurately, which may lead to poor control performance and even instability in operation of the MPC strategy. The existing robust control approaches are generally too conservative, and may not be suitable for use in real-world buildings.

In this study, the advantages of neural networks (NNs) will be exploited to address the challenges outlined above. NNs are known as universal approximators, meaning that they can model any continuous functions with any desired degree of accuracy. In particular, the NNs will be used to conduct modelling work, generate control rule, and improve the performance of classical MPC. The major contributions of this thesis are presented in four chapters, with each based on an individual scientific paper.

Paper-1 presents a systematic modelling method for air handling units (AHUs) and thermal zone using a recursive NN (RNN). As the major novelty, a cascade NN structure is developed, which enables the thermal dynamics modelling of both interior zones and perimeter zones within investigated building. This approach allows accurate prediction of both supply air temperature and zone temperature prediction, making it suitable for predictive control design.

Continuing with the first paper, *Paper-2* introduces a multi-input, multi-output (MIMO) model, which effectively models the convective heat exchange between open spaces within multi-zone commercial buildings. The proposed model allows closed-loop prediction for several adjacent zones simultaneously by considering their thermal interaction. A NN-based optimal start-stop control method is also developed in this paper to demonstrate the energy saving potential enabled by using the proposed predictive model.

The NN models provide accurate prediction results, but they are in general difficult to optimise under an MPC framework. *Paper-3* presents a hybrid MPC (HMPC), which combines the classic MPC with an inverse NN model. With the HMPC, the classical MPC based on linearised building model optimises the supplied cooling energy. The inverse NN model compensates the nonlinearity associated with the AHU process and generates more accurate control inputs. Simulations and experiments demonstrate the feasibility of the proposed method in achieving energy and cost reductions while maintaining good indoor thermal comfort in the investigated large commercial building.

The MPC formulation in *Paper-3* does not take the system uncertainty into account. In reality, however, the modelled building energy systems are always affected by uncertainties, so that the modelling errors become inevitable which cause control performance degradation to the MPC. *Paper-4* considers the application of a robust MPC (RMPC) to handle the system uncertainty within buildings. In particular, an uncertainty estimator is developed based on the previously presented RNN model to provide uncertainty bound to the conventional closed-loop min-max RMPC. The newly developed bound estimator reduces the conservatism of the RMPC and achieves improved control performance.

In conclusion, the research work presented in this thesis has made important contributions to the research of intelligent model predictive control for air-conditioning systems in commercial buildings. The methodologies developed in this thesis can be utilised for other buildings or for the control of other dynamic systems.

Declarations

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Acknowledgements

First of all, I would like to extend my sincere gratitude to my supervisor, Dr Lei Chen who brought me into the interesting research filed. He has provided me with tremendous guidance and support during the PhD journey. His wisdom and diligence have helped me to overcome all the difficulties and to keep me on the right track. He has also encouraged me to engage in various activities to promote my research, from which I benefited a lot.

I would like to express my gratitude to Associate Professor Eric Hu who supervised me on a weekly basis. Eric has provided precious resources and great ideas in this study. He has also given me great encouragement which helped me to go through the hardest period of my research .

I would like to thank Dr Moterza Mohammadzaheri who was co-supervising this project during the first year of my PhD. He was always willing to share his experience and knowledge with the others, from where I have learned a lot.

In particular, I am grateful to Professor Robert Bidmead for his suggestions that have greatly inspired me and opened my eyes in conducting my research. I cannot go that far to implement my idea without his kind suggestions.

I feel very fortunate to have the opportunity to study and work in the School of Mechanical Engineering, University of Adelaide. I have received precious feedback and suggestions from other academic staff, who had illustrated me and helped me from many aspects. Also, many thanks to Ms Dorothy Missingham and Ms Alison-Jane Hunter for running the terrific writing workshop which improves my writing and speaking.

I would like to thank my PhD colleagues: Yangkun Zhang, Boyin Ding, Difang Tan, Da Sun and Fangtai Tan for those joyful time spending at the lab. I am grateful to Mr Yu Ouyang for his suggestions from industry point of view. His advice has helped me to conquer practical problems in the most effective way.

I would like to acknowledge Adelaide Airport Limited for providing financial support and experimental data for this study. Also, I show my great appreciation to Johnson Controls Australia Pty Ltd staff members: Trevor McGrath, Anthony Underwood and Dave Furniss, who had offered technical help and support in setting up the experiment platform and conducting experiment at T-1 building. Without their help and patience, the filed test could never be finished.

Finally, but foremost, I would like to express my great love and appreciation to my parents, who gave birth to me and supported me in my study. My eternal appreciation goes to my beloved wife, Fu Xie, who had gone through so much tough time with me. Her accompaniment, love and support have always been the energy of finishing my study.

List of Publications

This thesis is submitted as a portfolio of publications either published or submitted for publication by peer-reviewed journals according to the 'Academic Program Rules' of the University of Adelaide. The papers included in this thesis are all closely related to the field of the research of this work. This thesis is based on the following papers, which are referred to by their Arabic numerals:

Paper-1 Huang H., Chen L., Mohammadzaheri M., Hu E., "A New Zone Temperature Predictive Modeling for Energy Saving in Buildings", In Procedia Engineering, vol. 49, pp. 142 - 151, 2012.

Paper-2 Huang H., Chen L., Hu E., "A neural network-based multi-zone modelling approach for predictive control system design in commercial buildings", In Energy and Buildings, vol. 97, pp. 86 - 97, 2015.

Paper-3 Huang H., Chen L., Hu E., "A new model predictive control scheme for energy and cost savings in commercial buildings: An airport terminal building case study", In Building and Environment, vol. 89, pp. 203 - 216, 2015.

Paper-4 Huang H., Chen L., Hu E., "Reducing energy consumption for buildings under system uncertainty through robust MPC with adaptive bound estimator", *Submitted to Building and Environment*, 2015.

The following conference papers are of close relevance to the present work and are included in the appenices.

2013 Huang H., Chen L., M. Mohammadzaheri., Hu E., Chen ML., "Multi-zone temperature prediction in a commercial building using artificial neural network model", In Control and Automation (ICCA), 2013 10th IEEE International Conference on, pp. 1896-1901, 2013.

2014 Huang H., Chen L., Hu E., "Model predictive control for energy-efficient buildings: An airport terminal building study", In Control Automation (ICCA), 11th IEEE International Conference on, pp. 1025-1030, 2014.

2015 Huang H., Chen L., Hu E., "A hybrid model predictive control scheme for energy and cost savings in commercial buildings: Simulation and experiment", In American Control Conference (ACC), 2015, pp. 256-261, 2015.

Nomenclature

C_z capacitance associated with the fast-dynamic masses (kJ/°C)

C_w capacitance associated with the slow-dynamic masses (kJ/°C)

C_a specific heat of air (kJ/kg°C)

C_{cw} the overall thermal capacity of the chilled water and metal body of cooling coil (kJ/°C)

C_{pw} specific heat capacity of chilled water (kJ/°C)

CO_2 carbon dioxide concentration (ppm)

D_{out} outdoor air damper opening level (%)

A area of the solid surface (m^2)

f_w chilled water flow rate (l/s)

f_{cw} chilled water flow rate (l/s)

H_r relative humidity (%)

T thermal node temperature (°C)

T_c chilled water temperature (°C)

T_{sp} set point temperature (°C)

T_{oc} temperature constraints during occupied hours (°C)

T_{uc} temperature constraints during unoccupied hours (°C)

T_{cwo} outflow water temperature (°C)

T_{ao} discharge (outflow) air temperature (°C)

T_{cwr} return chilled water temperature (°C)

T_{cws} supply chilled water temperature (°C)

T_{ai} temperature of the air going into the cooling coil (°C)

m_w water mass-flow rate of the cooling coil (kg/s)

$\dot{m}$ mass flow rate of the supplied air (kg/s)

P_c power consumption of cooling energy consumed by the cooling coils (kW)

P_f power consumption of supply fan (kW)

Q_{chil} cooling load of the building (kW)

Q_f supplied free-cooling energy (kW)

Q_c supplied cooling coil energy (kW)

Q_s heat gain generated by solar radiation (W)

Q_p heat gain generated by occupancy (W)

Q_{leak} heat gain caused by the leakage of the zone (W)

R thermal resistance associated with walls, window or floor (°C/W)

R_c convective heat transfer coefficient between adjacent zones (°C/W)

R_w convective heat transfer coefficient associated with the air node and surface of the wall (°C/W)

R_{win} convective heat transfer coefficient through window (°C/W)

R_f convective heat transfer coefficient associated with the floor (°C/W)

S_r global horizontal irradiation (W/m^2)

U overall heat transfer coefficient (kJ/m^{2}K)

h convective heat transfer coefficients per unit area (W/m^{2}K)

V_c chilled water valve opening level (%)

V_{cw} chilled water valve opening level (%)

V_z volume of the zone (m^3)

Δt sampling time of the building data (s)

n_a, n_b orders of the input variable

r order of the system

n_k time delay of the input variable

f nonlinear neural network function

ρ density of the air (kg/m^3)

k time delay of the input variable

w uncertainty

Subscripts

i indices for zones

sa supply air

r return air

out outdoor air

w walls and ceiling

g windows

f floor

N prediction horizon

k time step

cws supply chilled water

cwr return chilled water

Abbreviations

COP Coefficient of Performance of the chiller plant

MPC Model Predictive Control

HMPC Hybrid Model Predictive Control

MIMO Multi-input, Multi-output

HVAC Heating, Ventilating, and Air Conditioning

BMS Building Management System

AHU Air Handling Units

CAV Constant Air Volume

VAV Variable Air Volume

ANN Artificial Neural Network

RNN Recurrent Neural Network

RMPC Robust MPC

ARMPC Adaptive Robust MPC

SMPC Stochastic MPC

BC Baseline Control

RC Resistance Capacitance

OSSC Optimal Start-Stop Control

TOU Time-of-Use

LTI Linear Time Invariant

PMV Predicted Mean Vote index

NARX Nonlinear Autoregressive models with exogenous input

ARMAX Autoregressive Moving Averagemodel with exogenous inputs

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