Model predictive coordinated control method for non-uniform indoor temperature environment with VAV system

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Abstract

In the control of Variable Air Volume (VAV) terminals in traditional VAV system, the temperature of one thermostat is used to represent the room temperature. The monitoring by only one thermostat on the zonal ambient temperature has weakened the holistic effect of HVAC control system due that the one thermostat cannot accurately reflect the temperature of each zone, which caused the HVAC control hardly satisfies the dynamically changing and varying demands from different thermal zones. Thus, the traditional SISO feedback control algorithm needs great improvements to meet diverse temperature preference and non-uniform temperature distribution for multiple thermal zones supplied by a VAV system, with the consideration of mutual influence of airflow from each VAV terminal.

For the common situation of a large open office with multiple VAV terminals, this paper proposes an open-loop air flow rate predictive coordinated control method based on MATLAB-Simulink platform. A closed-loop Model Predictive Control (MPC) correction method is proposed and combined to the air flow rate predictive coordinated control system. All thermostats and diffusers are connected in one control system. The air flowrate of each diffuser is coordinated supplied according to the diverse temperature preference. The accuracy of complete control system is validated with 500 random cases. The results show that the model predictive coordinated control system with correction can sufficiently satisfy different temperature preference under the dynamic changing of the non-uniform temperature environment. The quantile 10% of control error percentage is -2.68% while the quantile 90% of control error percentage is 2.26%, and the temperature control error of each thermostat is within -1°C~1°C.

Highlights

- Model predictive coordinated control for different diffusers
- Real-time closed-loop MPC error correction system to ensure the control accuracy
- Diverse temperature preference sufficiently satisfied under the dynamic changing of the non-uniform temperature environment

Introduction

In the control of terminals in traditional VAV system, the temperature of one thermostat is used to represent the room temperature, and the indoor thermostat is usually installed at the entrance of the room or on the wall around the room. Actually, the indoor temperature is non-uniform affected by dynamic outside environments, non-uniform internal load distribution, and varying indoor airflow patterns (Wu, 2020; Shuai, 2020). The temperature monitored by the thermostat cannot accurately reflect the temperature of each thermal zone, which affects the control effect of HVAC system and hardly satisfies the diverse temperature preference. If thermostats can be installed in different thermal zones, the indoor temperature distribution can be collected to better reflect the real indoor temperature condition, and can be fed back to the VAV control system to achieve more effectively indoor environment control. Meanwhile, thermostats installed in each thermal zone can meet the independent microenvironment demand of occupants.

In traditional VAV system, one thermostat corresponds to one VAV terminal. When the setpoint or the measured of the thermostat change, its corresponding VAV terminal adjusts the air flowrate to make the measured temperature be equal to its setpoint. Thus, it is a typical single-input, single-output(SISO) feedback control system (Kang, 2014; Zhou, 2014). This control system can well meet the indoor temperature requirements of control for the small room with uniform temperature distribution. As the cooling capacity of a single VAV terminal is limited, multiple VAV terminals are needed for large-open office room. If only one thermostat is used to control all VAV terminals, it is difficult to choose the appropriate thermostat installation location because of the large room area and non-uniform temperature distribution, leading to the poor temperature control quality in the room. On the other hand, the airflow from different diffusers has mutual influence within a certain distance. The temperature of one location is determined by the integrated air flowrate of the surrounding diffusers. If SISO feedback control method applied to large room, one VAV terminal adjusts the air flow rate according to one thermostat, separately. The mutual influence among different diffusers is ignored. If multiple terminals adjust the air flowrate according to multiple setpoints of thermostats simultaneously, or when the measured temperature of a thermostat changes, its surrounding terminals adjust the air flowrate...
simultaneously, the temperature of all thermostats in the room will be ensured. Meanwhile, the setpoints of different thermostats are probably different due to diverse temperature preference of occupants. To summarise, it is difficult to satisfy non-uniform temperature distribution demand with conventional feedback control system.

In large open office space, the non-uniform distribution of indoor temperature is especially obvious, if the room is divided into multiple thermal zones, and one thermostat and one diffuser are installed in each zone, when the outdoor environment, internal load density or any thermostat setpoint changes, how to real-time adjust the airflow of each terminal with the consideration of mutual influence between different terminals to achieve human-centered micro-environment temperature control is an urgent research problem to be solved.

Therefore, this paper proposes a model predictive coordinated control and real-time error correction method for non-uniform indoor temperature environment and the control method is validated based on MATLAB-Simulink simulation platform. The supply air flowrate of each diffuser is coordinated control according to the diverse temperature preference in different thermal zones, so the indoor non-uniform temperature field is built to meet the diverse temperature preference.

This paper constructs as follows. Section 2 explains the research framework, method of control system and correction system. Section 3 includes the results of control system and correction system. Section 4 is the conclusion.

**Methods**

Figure 1 shows the framework on model predictive coordinated control method combined with error correction method for non-uniform indoor temperature environment in this paper.

First of all, operation data required for the study is collected from a real room, as model prediction control method required, the Air Flowrate Prediction Model is constructed using the machine learning algorithm. Then the open-loop model predictive coordinated control system is simulated on the MATLAB-Simulink platform.

In order to improve the control accuracy of the open-loop control system, a real-time error correction system is added to the control system, and the Static Room Thermal Response Model is developed and connected to the correction system to predict the room temperature and temperature control error in advance, correction value is calculated and fed back to the setpoints of thermostats. Finally, with the closed-loop error correction method, the model predictive coordinated control method for the indoor non-uniform temperature environment is determined.

The special feature of this control method is that the thermostats and diffusers do not need to be installed one-to-one correspondence, even the number of thermostats can be more than the diffusers. All thermostats and diffusers are connected in one control system. The location of the diffusers can be conventionally designed, while the thermostats can be installed near the occupants. Occupants can adjust the setpoint of thermostats nearby, then the air flowrate of diffusers can be adjusted according to coordinated control method, the closed-loop real-time error correction system can sufficiently satisfy the diverse temperature preference and accurately ensure the indoor non-uniform temperature environment.

**Results**

**Data Preparation and collection**

In this paper, a large-open office actual room with VAV system is selected to collect the operation data. As shown in Figure 2, 8 square diffusers are regularly installed on the ceiling and 11 thermostats are installed on the height of 1.2m, of which 8 thermostats are evenly installed along the surrounding walls, and 3 thermostats are evenly installed in the central of the room, which can accurately collect non-uniform temperature distribution of the 1.2m height plane.

**Figure 1: Framework of this paper.**

**Figure 2: Top view of diffusers and thermostats in the room.**

Considering the main factors affecting the indoor non-uniform temperature distribution are outdoor dry bulb temperature, internal loads, supply air temperature and...
supply air flowrate (Abir, 2021; Wu, 2020). We collect the operation data including outdoor dry bulb temperature, internal loads density, supply air temperature, supply air flowrate of each diffuser and temperature of 11 thermostats every 10 minutes. First, 2000 sets of data were collected to build the original data-driven model, and then the data continued to be collected to run for subsequent model optimization and updating. Finally, 20000 sets of operation data are collected and the value information is listed in Table 1.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor dry bulb temperature ($T_{db}$/°C)</td>
<td>25-38</td>
</tr>
<tr>
<td>Supply air temperature ($T_{sa}$/°C)</td>
<td>15-19</td>
</tr>
<tr>
<td>Internal loads density ($P_{room}$/ W/m²)</td>
<td>9.54</td>
</tr>
<tr>
<td>Supply air flowrate of 8 diffusers ($Q_{d}$/m³/h)</td>
<td>65-390</td>
</tr>
<tr>
<td>Temperature range of 11 thermostats among all cases (°C)</td>
<td>19.2-29.5</td>
</tr>
<tr>
<td>Temperature difference between 11 thermostats in each case (°C)</td>
<td>0.4-3.0</td>
</tr>
</tbody>
</table>

Table 1: Value of operation data.

Emulation of MPC coordinated air flowrate control system
Model predictive control (Ferreira, 2012; Afram, 2017) is to predict the future state of the system by using a system model, while the model used is called a predictive model. In this paper, we use the prediction model to predict the air flowrate of 8 diffusers, and the predicted air flowrate is used as the setpoint of the damper, thus the demand of the non-uniform temperature distribution in the room can be achieved. The MPC coordinated air flowrate control system mainly consists of three parts: Air Flowrate Prediction Model, damper controllers and damper actuators. As shown in Figure 3, it is an open-loop control system. As the Air Flowrate Prediction Model predicts the air flowrate of 8 diffusers based on the environmental parameters (outdoor dry bulb temperature, internal loads density, supply air temperature) and the temperature setpoints of 11 thermostats, all thermostats and all diffusers are connected in one control system, it is a multi-input, multi-output (MIMO) coordinated control system. Besides, the airflow from every diffuser will affect each other within a certain distance. Therefore, the air flowrate of every diffuser needs to be controlled in a coordinated rule to satisfy the non-uniform thermal demand in the room, while the MIMO Air Flowrate Prediction Model predicts the air flowrate of all diffusers simultaneously to realize the coordinated control among all diffusers. The Air Flowrate Prediction Model is regarded as a black box model in this paper. The collected operation data set is randomly divided into training set and test set according to the ratio of 9:1. Based on MATLAB, two different types of machine learning algorithms, multi-input single-output (MISO) and multi-input multiple-output (MIMO), are used to construct the Air Flowrate Prediction Model. The Environment Variable $\bar{E}_{nv}$ (Outdoor Dry Bulb Temperature $T_{db}$, Supply Air Temperature $T_{sa}$, Internal Loads Density $P_{room}$) and the Indoor Temperature Variable $\bar{T}$ (Temperature of 11 thermostats $T_{t} \sim T_{t11}$) are defined as the input variables, while Supply Air Flowrate Variable $\bar{Q}$ (Supply Air Flowrate of 8 diffusers $Q_{d} \sim Q_{d8}$) is defined as the output variable. The standard deviation of the testing set error, the prediction error percentage, the training time and robustness are chosen as evaluation indicators. Finally, the model developed by MIMO-CNN (Convolutional Neural Networks) method has the best prediction accuracy.

As rolling optimization is the core of predictive control, so when more operation data is collected, the Air Flowrate Prediction Model can be rolling optimized to improve the accuracy of the MPC control system.

Figure 4 shows the schematic of the damper model in the control system. The predicted air flowrate of each diffuser is set as the setpoint of each damper controller, then the opening of each damper is adjusted by the actuator, meanwhile the actual air flowrate of each diffuser is measured as the feedback of the controller, the air flowrate is controlled in closed loop to ensure the supply air flowrate is equal to its setpoint. The Proportion Integration Differentiation (PID) controller system of the damper in Simulink is shown in Figure 5, and the actuator system of the damper in Simulink is shown in Figure 6.

Figure 3: Schematic of MPC control system.

Figure 4: Schematic of the damper model.
the room is considered as the series composition of a Static Room Thermal Response Model (the relationship between air flowrate input and temperature output) and a dynamic response element (thermal inertance of room air). When the air flowrate of any diffuser changes, the output of the Static Room Thermal Response Model changes immediately, but due to the thermal inertance of the room air, the output of the dynamic response element takes some time to reach the steady-state value.

Similar to the Air Flowrate Prediction Model, the Static Room Thermal Response Model is regarded as a black box model (Alizadeh, 2018). The collected operation data set is randomly divided into training set and test set according to the ratio of 9:1. Based on MATLAB, two different types of machine learning algorithms, multi-input single-output (MISO) and multi-input multiple-output (MIMO), are used to construct the Static Room Thermal Response Model. The Environment Variable $\mathbf{Env} = (\text{Outdoor Dry Bulb Temperature } T_{odb}, \text{ Supply Air Temperature } T_{sa}, \text{ Internal Loads Density } P_{room})$ and Supply Air Flowrate Variable $\mathbf{Q}$ (Supply Air Flowrate of 8 diffusers $Q_1 \sim Q_8$) are defined as the input variables, and the Indoor Temperature Variable $\mathbf{T}$ (Temperature of 11 thermostats $T_1 \sim T_{11}$) is defined as the output variable. The standard deviation of the testing set error, the prediction error percentage, the training time and robustness are chosen as evaluation indicators. Finally, the model developed by MISO-SVM (Support Vector Machine) method has the best prediction accuracy.

**Figure 5:** PID controller of the damper model in Simulink.

**Figure 6:** Actuator of the damper model in Simulink.

**Inertial influence of Environment variables**

In actual system, the outdoor dry bulb temperature acts directly on the building envelope, while the building envelope has attenuation and delay effects on the heat transfer. The actual system will be reflected more realistically and accurately with the consideration of inertial effect of the building envelope. According to the fundamentals of heat transfer, the heat transfer through building envelope is an N-order inertial system, and the time constant in transfer function can be determined by the physical properties, thickness and surface characteristics of the envelope. In addition, the transfer function corresponding to the process of heat transfer from the indoor heat source to the indoor air can also be determined in the same way.

The inertia element of outdoor dry bulb temperature and internal load are added to the input of the Air Flowrate Prediction Model, respectively. Meanwhile, considering the actual change frequency of each input parameter, the sampling interval of outdoor dry bulb temperature is 1h, and the sampling intervals of supply air temperature, internal load density and temperature setpoints of 11 thermostats are 10min. The open-loop air flowrate prediction control system in Simulink is shown in Figure 7. Finally, 500 random cases are designed and used to validate the accuracy of control system. The parameters and results of 500 random cases are shown in Table 2 and Figure 8. Although the overall control error is not high but negative, and the temperature control error at local thermostats is more than -1°C. Therefore, a correction system is considered to improve the accuracy of the control system.
Figure 7: open-loop air flowrate prediction control system in Simulink.

Table 2: Parameters of 500 random cases and results of MPC coordinated control system without correction

<table>
<thead>
<tr>
<th>Parameters of 500 random cases</th>
<th>Outdoor Dry Bulb Temperature ($T_{odb}$/°C)</th>
<th>25-38</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply air Temperature ($T_{sa}$/°C)</td>
<td>15-19</td>
</tr>
<tr>
<td></td>
<td>Internal loads Density ($P_{cool}$/W/m²)</td>
<td>9-54</td>
</tr>
<tr>
<td></td>
<td>Temperature setpoints of 11 thermostats (°C)</td>
<td>21-29</td>
</tr>
</tbody>
</table>

Average of temperature differences of 11 thermostats (°C) 
-0.37

Average of Standard deviation of temperature differences of 11 thermostats 
0.84

Average of control error percentage (%) 
-1.31

Standard deviation of control errors 
0.026

Quantile 10% of control error (%) 
-4.55

Quantile 90% of control error (%) 
1.57

Figure 8: the temperature control error at local thermostats.

Emulation of real-time error correction system

Although the air flowrate control is a closed-loop system, the temperature control system is an open-loop system. Compared to common closed-loop control systems, open-loop control systems are much simpler in structure and also more economical, it can avoid many stability problems that usually exist in closed-loop control systems. However, the accuracy of open-loop control systems is generally lower than that of closed-loop control systems, and for open-loop control systems based on model predictive control, the control accuracy depends on the accuracy of the prediction model. Due to the limitation of the quantity and quality of data used for modelling, the model cannot be completely accurate and has limitation of generalization ability, which is reflected in the control accuracy as control error. When the error exceeds a certain limit, correction is required.

The general method of correction is to generate a suitable temperature correction value and add it to the input variable “the Indoor Temperature Variable” of the Air Flowrate Prediction Model.

As the measured temperature of 11 thermostats is the dynamic mixing response of the room air and supply air. If we can obtain steady-state temperature response just at the beginning of the control, the final control error can be calculated in advance. Thus, it is possible to do real-time...
correction to improve the control accuracy. Therefore, the Static Room Thermal Response Model is connected to correction system, the steady-state temperature response of 11 thermostats can be predicted in advance through model prediction, control error and correction value can also be calculated instantaneously. Figure 9 shows the schematic of MPC correction system.

![Figure 9: Schematic of MPC correction system.](image)

Figure 10 shows the test real-time error correction system. The dampers are ignored, assuming that the air flowrate setpoint is equal to the supply air flowrate. Conventional Proportional (P)/ Proportional-Integral (PI) algorithm is applied to generate the correction value. When the correction target is overall average error to be zero, either P algorithm or PI algorithm can be used, while when the correction target is minimum of sum of squared errors, only P algorithm can be used because the sum of square errors cannot be negative. To prevent the correction value from being too large to affect the normal operation of the system, the final correction value is limited to within \(-2^\circ C\). When the P algorithm is used, the correction value is also smoothed to prevent abnormal fluctuations in room temperature caused by sudden changes of the correction value. The results of different correction strategies are shown in Table 3. Global correction method and local correction method are included. The global correction method adds the same temperature correction value to setpoints of 11 thermostats, with the objective to reduce the overall average error. The local correction method only corrects the setpoint of individual larger error thermostat, with the objective to reduce the control error of individual thermostat. The reason for the poor effect of local correction method is that the MIMO Air Flowrate Prediction Model predicts the air flowrate of 8 diffusers according to setpoints of 11 thermostats. Even one setpoint is corrected, the predicted air flowrate of all diffusers will be changed at the same time and the control error of other thermostats will be affected. Therefore, local correction is not applicable in this control system. For global correction method, the result of the correction target of overall average error to be zero and PI algorithm is the best. Finally, the correction system is determined as a closed-loop real-time global error correction system.

![Figure 10: test system for real-time error correction.](image)

### Table 3: Results of test system for real-time error correction based on 500 random cases.

<table>
<thead>
<tr>
<th>Correction Method</th>
<th>Correction Parameter / Correction algorithm</th>
<th>Average of temperature differences of 11 thermostats (°C)</th>
<th>Average of Standard deviation of temperature differences of 11 thermostats</th>
<th>Average of control error percentage (%)</th>
<th>Standard deviation of control errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Correction</td>
<td>Overall average error / P Algorithm</td>
<td>-0.43</td>
<td>0.92</td>
<td>-1.562</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>Overall average error / PI Algorithm</td>
<td>-0.21</td>
<td>0.89</td>
<td>-0.680</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>Sum of squared errors / P Algorithm</td>
<td>-0.04</td>
<td>0.90</td>
<td>-0.048</td>
<td>0.017</td>
</tr>
<tr>
<td>Global Correction</td>
<td>Overall average error / P Algorithm</td>
<td>-0.08</td>
<td>0.90</td>
<td>-0.185</td>
<td>0.029</td>
</tr>
</tbody>
</table>
Air flowrate predictive coordinated control with closed-loop global error correction system

The complete control system is the combination of air flowrate prediction coordinated control system and the closed-loop global error correction system. Figure 11 shows the schematic and Figure 12 shows the Simulink system. Hourly typical meteorological data is used for outdoor dry bulb temperature.

![Figure 11: Schematic of complete system.](image)

![Figure 12: Complete system in Simulink.](image)

The comparison of control system with and without correction under 500 random cases is listed in Table 4. The result shows that the correction system effectively improves the control accuracy of non-uniform temperature distribution and satisfy the different temperature preference of occupancy. But the average of standard deviation of temperature differences of 11 thermostats almost is the same. The reason is that standard deviation of temperature differences of 11 thermostats is determined by the accuracy of Air Flowrate Prediction Model.

Figure 13~15 show the control effect of the correction system in detail. The average of control error percentage distribution is described in Figure 14. Figure 15 show the comparison result of temperature difference of control system with and without correction. The yellow part on the left is the result of control system without correction and the green part on the right is the result of control system with correction. The overall average error of the control system with correction is closer to 0 than that without correction, and the temperature control error of each thermostat is within -1°C~1°C.

<table>
<thead>
<tr>
<th>Table 4: Comparison of control system with and without correction for 500 random cases.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without correction system</td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>Average temperature differences of 11 thermostats (°C)</td>
</tr>
<tr>
<td>Average RMSE of temperature differences of 11 thermostats</td>
</tr>
<tr>
<td>Average control error percentage (%)</td>
</tr>
<tr>
<td>Standard deviation of control errors</td>
</tr>
<tr>
<td>Quantile 10% of control error percentage (%)</td>
</tr>
<tr>
<td>Quantile 90% of control error percentage (%)</td>
</tr>
</tbody>
</table>
Figure 13: control error percentage for 500 random cases.

Figure 14: Distribution of average of control error percentage.

Figure 15: Comparison of temperature difference of control system with and without correction.

Conclusion

This paper proposes an open-loop air flowrate predictive coordinated control method based on MATLAB-Simulink platform. Furthermore, a closed-loop Model Predictive Control (MPC) correction method is proposed and combined to the proposed air flowrate predictive coordinated control system. All thermostats and air diffusers are connected in one control system. The multiple thermostats can not only reflect the non-uniform indoor temperature environment, but also facilitate the occupants to adjust the ambient temperature according to their personal comfort. The air flowrate of each diffuser is coordinated supplied according to the diverse temperature preference. Besides, as more operation data is collected, the Air Flowrate Prediction Model can also be rolling optimized to improve the accuracy of control system.

The accuracy of complete control system is validated with 500 random cases. The results show that the model predictive coordinated control system with correction can sufficiently satisfy different temperature preference with the dynamic changing of the non-uniform temperature environment. The quantile 10% of control error percentage is -2.68% while the quantile 90% of control error percentage is 2.26%, and the temperature control error of each thermostat is within -1°C ~ 1°C.

References


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