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Integrated Control of RTUs and Refrigeration Equipment in Convenience Stores

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ABSTRACT

Convenience stores with refrigerated display cases are ubiquitous in much of the developed world. For such buildings it is common to utilize multiple rooftop units (RTU) to serve the retail area and multiple coolers or freezers to provide cooling for merchandise. The overall objective of this paper is to develop and assess an integrated control approach for typical convenience store applications using a virtual testbed. The integrated controls will coordinate the operation of multiple RTUs and refrigeration systems for the purposes of reducing energy consumption and electrical peak demand. For practical implementation, a model-based predictive control algorithm is developed and evaluated that requires no additional sensors. Convenience stores are everywhere and opportunities for optimizing controls would be significant.

1. INTRODUCTION

Retail stores with refrigerated display cases are ubiquitous in much of the developed world. An initial analysis of data from a (USA) retail directory indicates that there is approximately 3 billion square feet of buildings that incorporate both air conditioning and refrigeration equipment (big box super-centers, supermarkets, convenience stores, large drug stores, etc.) with approximate electrical energy consumption of 1283 trillion BTU per year (Michaels, 2003). This represents about 10% of the total electrical energy used in commercial buildings across the USA. A conventional control approach for these buildings relies on local feedback control, where each unit is cycled on and off using its own thermostat. Because a thermostat operates regardless of the overall building's behavior, the conventional control approach could result in unnecessary energy use and high electrical peak demand via poor coordination among the units. Therefore, significant energy savings and/or electrical peak demand reduction can be achieved by optimally coordinating both air conditioning and refrigeration equipment.

The goal of this paper is to develop and evaluate a practical control algorithm for on/off staging of multiple air conditioning and refrigeration units. A control approach, termed the Plug-and-Play (PnP) RTU Coordinator (Kim et. al. 2015a) which was previously developed to coordinate multiple rooftop units in an optimized manner, was generalized and extended for energy and demand savings in retail stores that include both air conditioning and refrigeration. In Section 2, the control algorithm is described. Section 3 describes a simulation testbed applied to a case study building. Results of controller evaluations for the store over the summer are provided in Section 4.

2. CONTROL APPROACH FOR RETAIL STORES

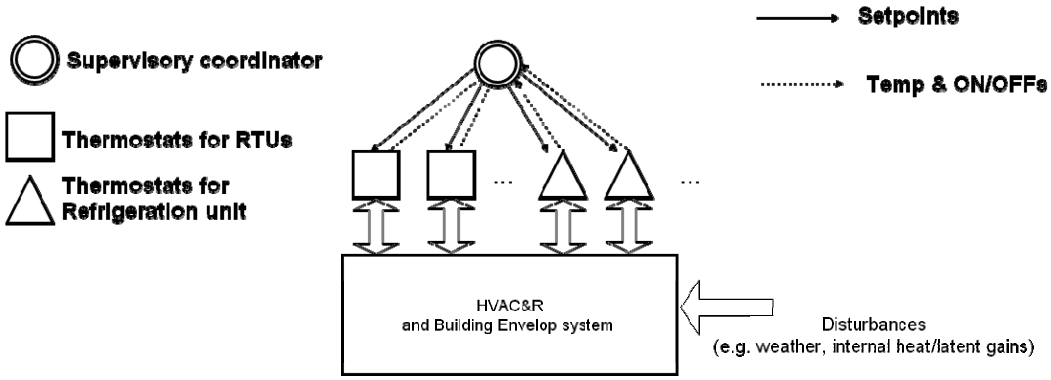

Figure 1: Unit coordinator elements and I/O for retail store applications

Since a conventional thermostat control approach does not consider overall building performance, it is natural to design a controller targeting reduction of energy consumption and peak demand in a centralized manner. Previously, a control algorithm coordinating an open space building served by multiple rooftop units (RTU) was developed and demonstrated. The control approach, termed the plug-and-play (PnP) RTU Coordinator (Kim et. al. 2015a), was designed to minimize the time required to configure the control strategy in order to enable a more cost effective control implementation for small/medium commercial building applications in which buildings are served by multiple RTUs. The control solution is not site-specific and provides reduced energy consumption and peak demand with low sensor requirements. Therefore, it is a strong candidate to provide energy/demand savings for retail store applications.

Due to its unique characteristic that it relies only on thermostat signals, i.e. temperatures and ON/OFF stage commands, the coordination algorithm can be directly applied to buildings equipped with both air handling and refrigeration units as depicted in Fig. 1. The RTU Coordinator has been slightly modified in order to apply to retail store buildings having refrigeration equipment. This is because the RTU Coordinator was designed for open space building applications while many retail store buildings, e.g. convenience stores, have separated zones served by different units. The algorithm details are explained as follows.

To formulate the control problem for optimal coordination between air conditioning and refrigeration units, let $p \in \mathcal{N}$ (a natural number) be the number of thermostats or equivalently the number of air conditioning and refrigeration units. The measured outputs are the thermostat temperatures, denoted as $y(k) \in \mathcal{R}^p$. The manipulated variables are the unit stages, denoted as $u(k) \in \mathcal{N}^p$. The control problem at a current time step k is:

$$\min_{u(j)\in\mathcal{N}^p,\delta\in\mathcal{R}^+,\Gamma_l\in\mathcal{R}^{p+},\Gamma_u\in\mathcal{R}^{p+}} \sum_{j=1}^{N_p}\sum_{i=1}^{p} P_i u_i(k+j) + d\cdot\delta + c_l^T\Gamma_l + c_u^T\Gamma_u \tag{1}$$

$$T_l - \Gamma_l \le E(y(k+N_p)\,|\,\mathcal{G}_k) \le T_u + \Gamma_u$$

$$\sum_{i=1}^{p} P_i u_i(k+j) \le \delta \quad (\forall j \in \{1,\cdots,N_p\})$$

where P_i is the rated power for ith unit, and hence the first term in the control objective represents a scaled energy consumption over a predicted horizon, N_p. $E(y(k+N_p)\,|\,\mathcal{G}_k)$ is the optimal N_p-step prediction given data $\mathcal{G}_k = \{y(k-1), y(k-2),\cdots,u(k+N_p-1),u(k+N_p),\cdots,u(k-1),u(k-2),\cdots\}$. T_u, T_l $(\in \mathcal{R}^p)$ are temperature upper and lower bounds, respectively. c_l, c_u $(\in \mathcal{R}^{p+})$ and d $(\in \mathcal{R}^{+})$ are weights on optimization variables of Γ_l, Γ_u $(\in \mathcal{R}^{p+})$ and δ $(\in \mathcal{R}^{+})$. From the last constraint, it can be seen that δ is an upper bound on each instantaneous electric demand over the prediction horizon. Therefore minimizing δ will naturally lower the electric peak demand over a prediction horizon. In addition, note that δ is dependent on all sequences of stages of p-units. Therefore, it is clear that the control problem supervises both air conditioning and refrigeration units. Γ_l and Γ_u can be seen as comfort violations from the first constraint of Eqn. (1). These variables are required to guarantee the existence of a solution for the optimization problem.

Note also that we only want to regulate the N_p-step ahead predicted temperatures within a temperature bound and not each of the predicted temperatures for less than the N_p steps. This is acceptable because our prediction horizon, N_p, is relatively short, e.g. 30 min to 1 hour. The N_p-step temperature regulation reduces the large number of inequality constraints that would be necessary if all of the predicted temperatures were constrained. The control problem of the RTU Coordinator can be obtained by eliminating δ, Γ_l and Γ_u in the objective function and constraints in Eqn. (1) (See Kim. et. al. 2015a). Therefore, the unit coordinator can be seen as a generalized version of the RTU Coordinator.

3. DEVELOPMENT OF CONVENIENCE STORE BUILDING MODEL

Figure 2: Google satellite view of the store

A simulation study was useful in evaluating the overall benefits of the unit coordinator compared with conventional control over a long period of time. This is because it was not possible to perform long-term side-by-side testing of the unit coordinator and conventional control for this site. A detailed model was developed and is briefly described in this section. This model was used as a virtual testbed to evaluate performance of the unit coordinator.

A convenience store (floor area 223.6 m^2, satellite view in Fig. 2) located in Acworth GA was identified as a case study building in collaboration with Oak Ridge National Laboratory and Emerson Climate Technologies. The store has four zones as shown in Fig. 3. The blue zone is the main customer service area served by two equivalent 3-ton rooftop units (RTU 1 and RTU 2). The green zone is a medium temperature walk-in refrigerated chamber served by two identical cooler units (< 2 ton) for beverages. The red zone is a low temperature (freezer) case having one unit (< 1 ton). The three refrigeration units have their own refrigeration equipment consisting of an outdoor air-cooled condensing unit and indoor evaporator coils. The pink zone is storage/office space served by one RTU (RTU 3).

Each unit is controlled by a separate thermostat shown as circles in the Fig. 3 (the thermostat locations for the storage and freezer are not shown).

A detailed model for the building was developed using a reduced-order coupled computational fluid dynamics (CFD) model (Kim et. al. 2015b). The model captures spatial temperature variations for open space areas, e.g. the main service and cooler zones in this building, in a computational efficient manner that allows long-term simulations. For a more detailed description, refer to Kim et. al. 2016. The model has been validated using measurements from the site. The occupancy profile was estimated by measuring percent door openings and was used to calculate occupant and lighting loads for occupied zones based on assumptions of maximum occupancy and nominal heat rates (ASHRAE, 2001).#

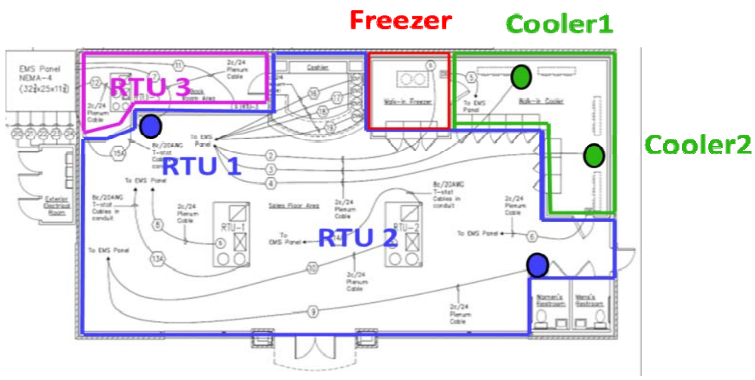

Figure 3: Zoning and unit numbering for a convenience store

4. RESULTS AND DISCUSSION

The simulation model described in Section 3 was executed in the Matlab Simulink environment with a stiff ordinary differential equation numerical solver, *ode15s*, that provides variable simulation time steps. The set-points for the conventional controls during an occupied period (6:00AM to 12:00AM) were set as (22^{o}C, 4^{o}C, -15^{o}C) for RTUs, coolers and freezer, respectively. Deadbands of 1^{o}C were used for all thermostats.

The unit coordinator controls predicted temperatures between 20 to 23^{o}C for RTUs, between 2 to 5^{o}C for coolers, and between -17 to -13^{o}C for the freezer, respectively. An ARX(3,2) model structure with two weeks of historical I/O data were used to establish the controller model for the unit coordinator. A 30-min look ahead horizon was used for the controller in this study. For the penalty terms of δ, Γ_l and Γ_u, 100, 1000 and 1000 were assigned in this simulation study.

A 5-minute sampling time was applied for both the conventional and unit coordinator controllers. The sampling time for the conventional control is to account for anti-cycling time for units to avoid too frequent cycling. A four-month simulation, from May to Aug, was performed for each controller with TMY3 data.

In a setting with multiple RTU's with different efficiency ratings, it's possible to save energy by increased use of the more efficient units. Since the two RTUs for the main service area are identical and two coolers are also identical, the primary expected benefit of coordination for this case is demand reduction. Fig. 4-5 show sample comparisons between the conventional and unit coordination controls from the four-month simulation results. The left hand side of the figures indicates the thermostat temperatures and the right hand side indicates the unit staging for the controls. For the conventional case, all units cycle significantly during the day due to part-load conditions. There are some situations where 5 units are operating at the same time resulting in high peak power consumption. An example can be seen at around 2:00 PM in Fig. 4. The total HVAC power at this time is around 15 kW as shown in the left hand side of Fig. 6.

However, the Unit Coordinator algorithm predicts 30-min ahead and supervises unit stages that can bring the zone temperatures within the comfort bounds with the minimum peak power for the 30-min ahead prediction period. This coordination can be seen in Fig. 5. When there is a need for operating several air conditioning units at the same time, e.g. marked as red dashed lines in Fig. 5 where both RTU1 and RTU2 were turned on, the coordinator adjusts sequences of stages of refrigeration equipment in order to reduce electric peak demand. This reduces the peak demand from 15 kW to 9 kW as shown in Fig. 6. Of course, when the cooling load is close to full capacity, there is no opportunity for demand reduction. However, in practice, units are selected to meet a peak load that may occur for only a few days a year and units work under a part-load condition for most times. This means there is significant peak demand reduction potential in most cases with greater potential.

Due to balancing between reduction of peak demand and comfort violations (difference in thermostat temperatures from desired setpoints) of the unit coordinator as shown in Eqn. (1), comfort violations for the unit coordinator are slightly higher (around 1°C) than for the conventional thermostat algorithm. However, the magnitudes of the violations are in an acceptable range as shown in Fig. 5, since the unit coordinator also tends to minimize the comfort violations.

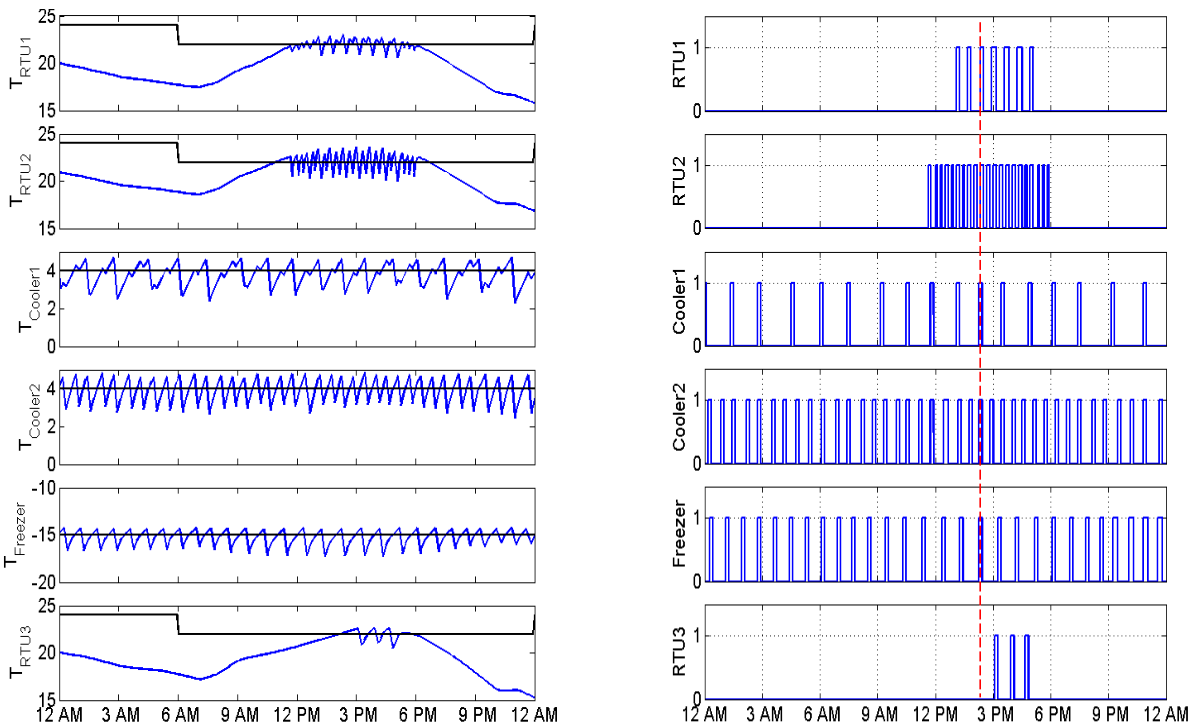

Figure 4: Representative RTU cycling and associated thermostat responses for conventional control at a convenience store

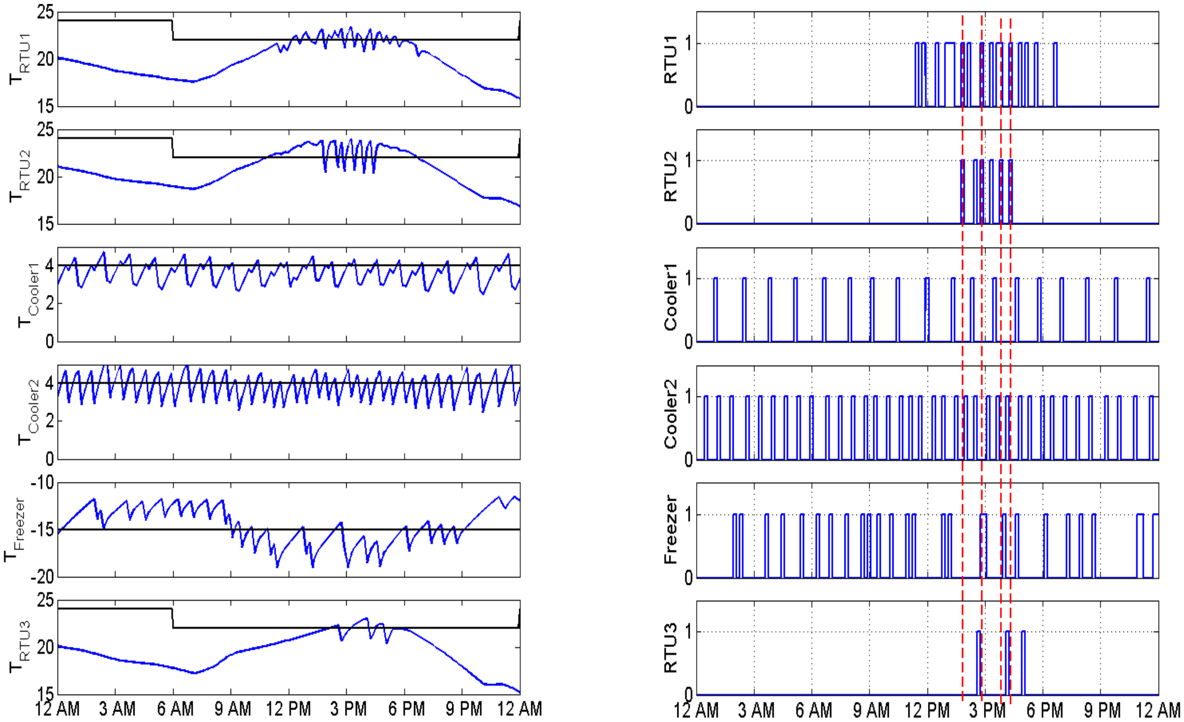

Figure 5: Representative unit cycling and associated thermostat responses for unit coordinator at a convenience store

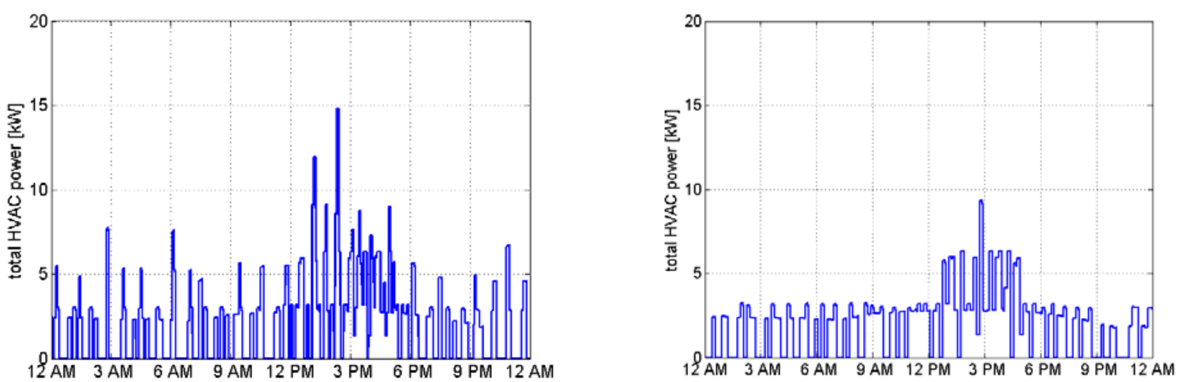

Figure 6: Profiles of total HVAC&R power for conventional (left) and unit coordinator (right) at a convenience store

Comparisons of energy usage and peak demand between the conventional and unit coordinator for the summer season are summarized in Table 1. Peak demands were calculated after performing a 15-min moving average on instantaneous power profiles for the simulation period. As expected, the energy savings are small due to lack of diversity in unit efficiencies. The primary energy savings are due to reduced cycling losses. However, the benefit of peak demand reduction is significant. The demand savings for the unit coordinator at the convenience store for the summer season are about 18 %.

Table 1. Cooling Season Comparisons for a convenience store

	May		June		July		August		4-Month Totals	
	Conv	PnP	Conv	PnP	Conv	PnP	Conv	PnP	Conv	PnP
Energy (MWh)	2.3	2.2	3.5	3.2	3.9	3.5	3.9	3.6	13.6	12.5
Peak Power (kW)	13.0	11.8	14.8	11.7	14.8	11.7	14.3	11.7	56.9	46.9
Energy Savings (%)		4.3		8.6		10.2		10.2		8.1
Peak Demand Cost Reduction (%)		9.2		20.9		20.9		18.2		17.6

5. CONCLUSIONS

A practical control algorithm for coordinating both air handling and refrigeration equipment was developed and evaluated using a simulation testbed for a convenience store in terms of energy and demand savings. The simulations allowed evaluations of savings for the unit coordinator compared to conventional control over an entire cooling season. Based on these evaluations, typical cooling season energy and peak demand savings are expected to be about 8 % and 18 %, respectively. The controller was designed to minimize implementation costs in that it does not require additional sensors and is self-learning. It can be generally applied to retail stores served by multiple air handling and refrigeration units.

NOMENCLATURE

RTU	rooftop unit
y	Thermostat temperature
u	unit stage
p	the number of units
k	current time step
N_p	prediction horizon
P_i	rated power for ith unit
T_u	temperature upper bound
T_l	temperature lower bound

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